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FREEZE-THAW DURABILITY AND AIR VOID PARAMETERS OF SOME CONCRETES

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Freeze-thaw Durability and Air Void Parameters of Some Concretes" submitted by Peter B. Makowichuk in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Studies on the determination of air void parameters by microscopic analysis of polished concrete sections were correlated with freeze-thaw durability tests in order to compare the durability characteristics of concrete made using high early strength cement, normal portland cement and normal portland cement with calcium chloride added as an accelerator.

The results indicate that for a curing period of fourteen days the use of high early strength cement and the use of calcium chloride treated cement affects freeze-thaw durability in two ways. First, the increased rate of hydration proves beneficial as it provides the concrete with a higher strength at an earlier age. Second, the addition of calcium chloride and the use of high early strength cement results in an inferior air void system in the concrete which lowers the freeze-thaw durability.

The change due to calcium chloride on the amount of hydration and on the air void system varies with the water cement ratio. Thus at high water cement ratios, the increases in the amount of hydration by the addition of calcium chloride or by the use of high early strength cement is great enough to offset the detrimental change in the air void system, and there is no significant change in durability. However at the lower water cement ratios the increase in amount of hydration is less and the detrimental effects on the air void system are more pronounced so that the durability is lowered considerably.

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GLOSSARY OF TERMS ON CEMENT AND CONCRETE TECHNOLOGY USED IN THIS REPORT

ADMIXTURE A material other than water, aggregates and portland cement (including air-entraining portland cement and portland blast-furnace slag cement) that is used as an ingredient of concrete and is added to the batch before or during the mixing operation.

AIR CONTENT - A - The amount of air in mortar or concrete, exclusive of pore space in aggregate particles, usually expressed as a percentage of total volume of mortar or concrete.

APPARENT AIR CONTENT The amount of air in mortar or concrete including voids within particles of aggregate. This term is obtained directly from an air content determination on fresh concrete by the pressure air meter.

AIR ENTRAINMENT The occlusion of air in the form of minute bubbles during the mixing of concrete or mortar.

AIR ENTRAINING AGENT An addition for hydraulic cement or an admixture for concrete or mortar which causes air, usually in small quantity, to be incorporated in the form of minute bubbles in the concrete or mortar during mixing, usually to increase its workability and frost resistance.

AIR VOID A small space enclosed by the cement paste in concrete and occupied by air. This term does not refer to capillary or other openings of submicroscopical dimensions or to voids within particles of aggregate. Air voids are almost invariably larger than 2 microns in diameter. The term includes both "entrapped" and "entrained" air voids.

ENTRAPPED AIR VOID These are air voids normally present in intergranular spaces in the cement and aggregate. These voids characteristically are 1 mm. or more in diameter and irregular in shape because the periphery of the void follows the contour of the surrounding aggregate particles.

ENTRAINED AIR VOIDS Air voids resulting from air entrainment. These voids typically are between 10 and 1000 microns in diameter and spherical or nearly so because of the hydrostatic pressure to which they are subjected by the surrounding paste of water, cement and aggregate fines.

WATER VOID (WATER CAVITY) These are relatively large irregular openings resulting from bleeding and settlement of fresh concrete. They generally are found directly below larger sized aggregate and in mature concrete appear dry as a result of the curing and hydration process.

PASTE CONTENT - p - The proportional volume of cement paste in concrete, expressed as a percentage of the volume of the hardened concrete, calculated as the simple summation of the proportional volumes of the cement and water included in the concrete mixture.

SPACING FACTOR - L - A useful index related to the maximum distance of any point in the cement paste from the periphery of an air void, in inches.

SPECIFIC SURFACE - α - The surface area of the air voids in hardened concrete, expressed as square inches per cubic inch of air void volume.

CHORD INTERCEPT - $\bar{l}$ - The average length of chord across the cross-sections of the air voids intercepted by a line of microscopical traverse, in inches.

CHAPTER I

INTRODUCTION

Adequate durability under conditions of service is one major requirement common to all concrete products and structures. During recent years, the increased use of salts for snow and ice removal, and the increased quantity of concrete poured during late fall and winter seasons has presented new problems in durability.

Studies on air-entrained concrete were initiated as early as 1937 by the Portland Cement Association. These tests and numerous others have shown that concrete having an air content in the range of 3 to 6 per cent by volume is definitely superior to non-air-entrained concrete in regard to surface scaling effects due to de-icing salt application and also due to repeated cycles of freezing and thawing.

Late fall and winter construction presents extra problems in concrete work. Fresh concrete must be protected from freezing and given adequate curing in order to develop necessary strength under conditions of low atmospheric temperatures. Various methods are available to accelerate the curing process in order to ensure that the required strength at an early age might be obtained. The most common practice in Western Canada is the use of high early strength cement or the addition of calcium chloride to act as an accelerating agent.

The A.C.I. Standard, "Recommended Practice for Winter Concreting (A.C.I. 604-56)" states that air-entrained concrete and additions of 1% calcium chloride by weight of cement are recommended in cold weather (40° F.). However, for freezing temperatures, amounts up to 2% and 3%

calcium chloride by weight of cement are added in order to obtain the increased rate of hydration that is desired at the lower temperatures.

The effect of calcium chloride as an admixture in concrete on the freeze-thaw durability properties is not well understood and there is a very limited amount of literature available on this topic. In a recent paper Richard C. Mielenz, et al (1957)*, stated, "The addition of 1% calcium chloride to air-entrained concrete resulted in larger entrained air bubbles and a higher spacing factor. Since calcium chloride is generally used in cold weather, the cumulative adverse effects on bubble size and spacing factor may be increased appreciably with possible serious effects on freezing and thawing resistance." The "cumulative adverse effects" referred to by Mielenz, et al include effects of varying temperature and slump as well as the addition of calcium chloride.

In view of the extensive use of calcium chloride in winter concreting in this area and the limited knowledge pertaining to its effects on freeze-thaw durability of concrete, and particularly in view of Mielenz's remarks pertaining to the possible adverse effects, a program was set up to compare the freeze-thaw durability of concrete made using normal cement, high early strength cement, and normal cement plus calcium chloride as an accelerator. Air-entrained and non-air-entrained concrete mixes were designed using local materials and tested for compressive strength and freeze-thaw durability as well as examined microscopically to determine the air content and air void parameters.

The scope of this report was to inquire into the physical relations

*References are cited by indicating the author and the year of publication. A complete list of references used is contained in the Bibliography at the end of the thesis.

obtained by the laboratory investigation. Limitations imposed on the results by the use of accelerated laboratory freeze-thaw tests and other laboratory conditions should be considered before application of any of the conclusions to actual field practice.

The preliminary part of this report reviews the present literature available with emphasis on the basic theories and principles pertaining to freeze-thaw durability. Following an outline of the test program, the discussion of results attempts to parallel the findings with the basic theories. Conclusions and recommendations are presented in the final chapter.

CHAPTER II

FUNDAMENTAL THEORY RELATED TO FREEZE-THAW DURABILITY

2-1 GENERAL

Concrete has been described as a pseudo-solid because it does not behave as proper solids do (T.C. Powers 1958). The reasons for its special kind of behavior have been the object of many investigators. Studies on the physical structure and properties of cement paste and concrete have lead to new approaches in the study of durability (T.C. Powers 1945, 1948, 1949, 1958). These new approaches to concrete durability emphasize the very important role played by water in the deterioration of concrete and also the equally important role played by the pore structure of the hardened concrete.

The physical effects of freezing may be different in different components of concrete. Freezing may damage the paste leaving the aggregate undamaged, or alternately, freezing may damage the aggregate particles with resulting damage to the paste. In any case damage arises either from dilation of the paste, or from dilation or breakage of rock particles or from both.

Freezing of a porous body may cause damage by the following pressure producing mechanisms, (1) displacement of water from freezing site (hydraulic pressure), (2) movement of water to freezing site, producing osmotic pressure and microscopic segregation of ice, (3) movement of water to the freezing site producing macroscopic segregation of ice.

Theories based on mechanism (1) and (2) seem to account for all phenomena in mature concrete that is not too permeable. For mature

concrete of relatively high permeability and low strength, and in green or fresh concrete, mechanism (3) is applicable.

2-2 STRUCTURE OF HARDENED PORTLAND CEMENT PASTE

The chemical reactions of the components of portland cement with water are referred to as cement hydration. The resultant hardened mass of the hydration process is referred to as hardened portland cement paste.

Hardened portland cement paste is composed of the following components.

(1) unhydrated clinker
(2) calcium hydroxide
(3) cement gel
(4) capillary cavities

Of these the most predominant one, microscopically amorphous, is cement gel. It is composed of gel particles and interstices among those particles called gel pores. The Brunauer-Emmett-Teller method of determining specific surface gives the specific surface of the solid part of the gel as about 700 m^2 per $cm.^3$ of solid which is equal to the specific surface of closely packed spheres having an average diameter of 86 Angstrom units (T.C. Powers 1958).

The structure of cement paste includes gel, crystals of calcium hydroxide, some minor components, residues of the original cement and residues of the original water-filled spaces in the fresh paste. These residual, submicroscopic, originally water-filled spaces are called capillary pores, or capillary cavities. Air bubbles in a specimen are not considered as part of the paste, but as a separate component of the specimen.

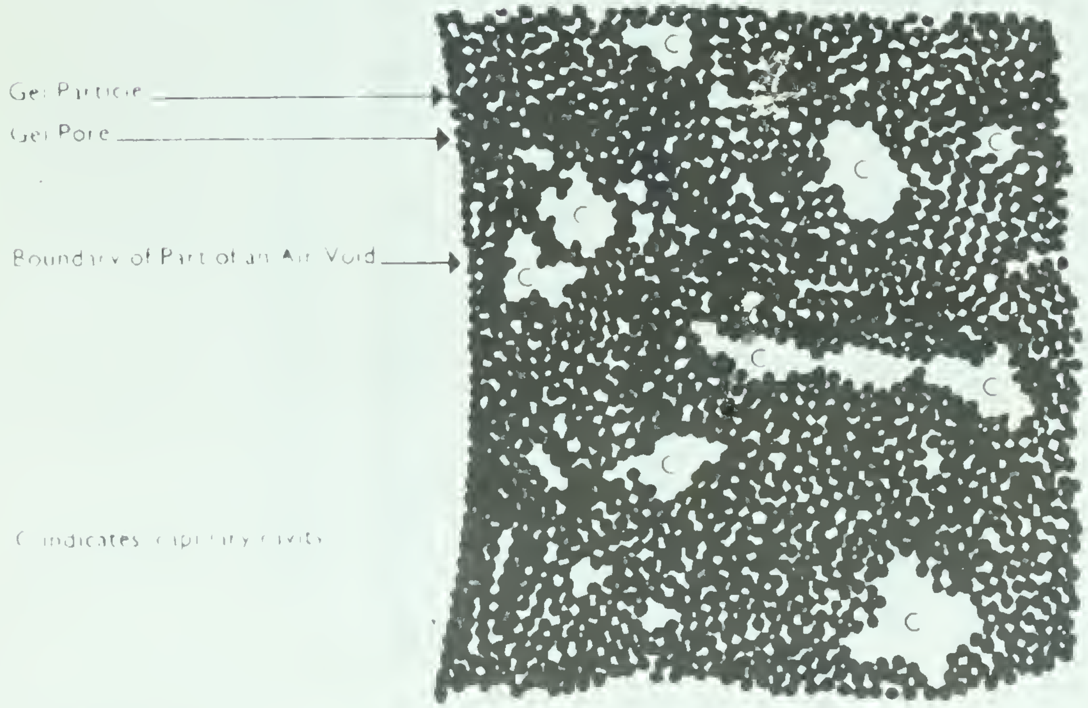

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Fig. A Simplified diagram of paste structure. C indicates capillary cavity.

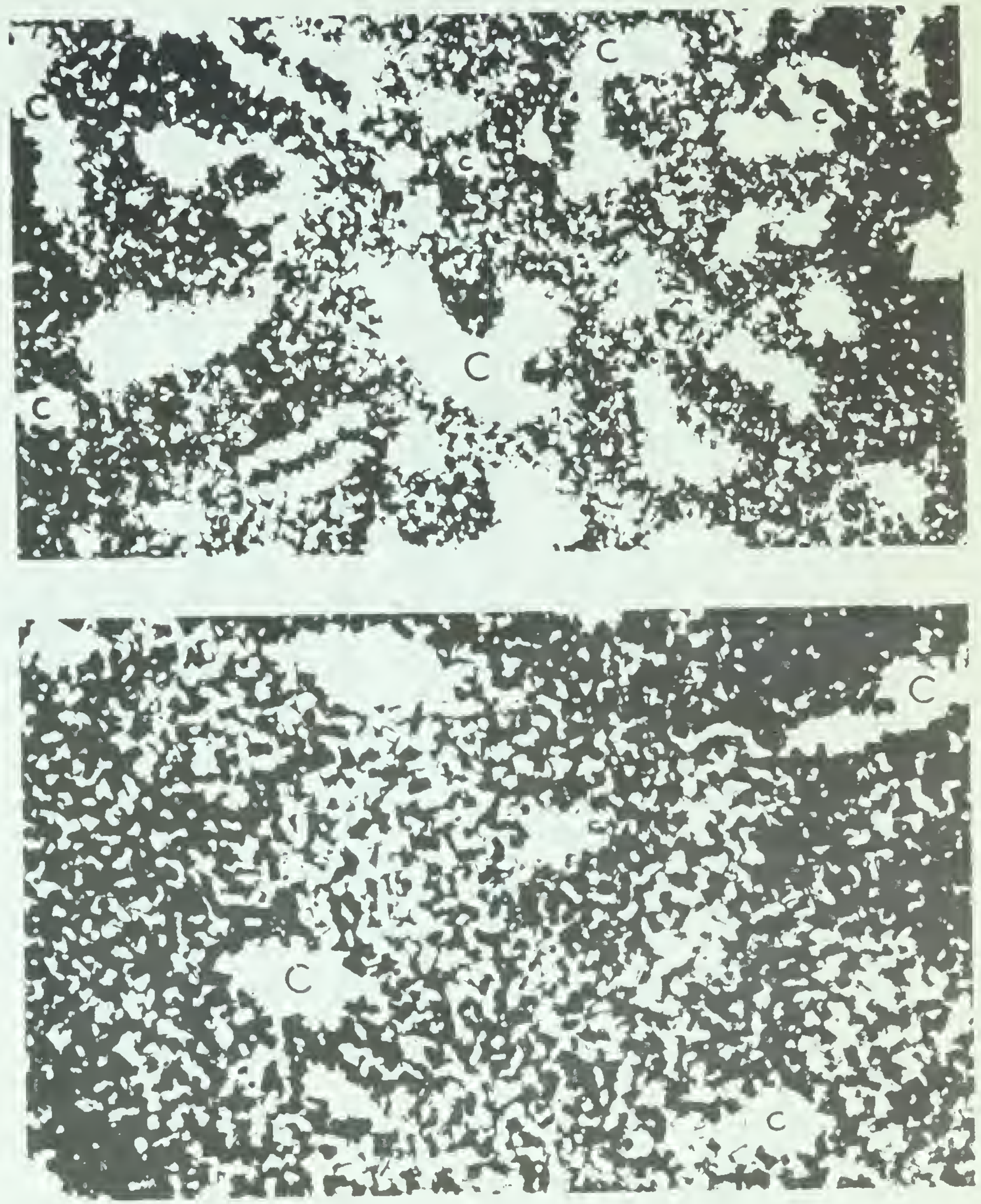


FIGURE **B** *Simplified model of paste structure*

Masses of randomly oriented groups of black lines represent cement gel. Spaces like those marked C represent capillary cavities. Upper drawing represents mature paste, w/c = 0.5, capillary porosity 20%; lower drawing represents nearly mature paste, w/c = 0.3, capillary porosity 7%.

FIGURE 1.

Thus two classes of pores within the boundaries of a body of paste are recognized; (1) gel pores, which are characteristic features of the structure of the gel, and (2) capillary pores or cavities representing space not filled by gel or other solid components of the system. FIGURE 1 shows two models of this concept of hardened cement paste structure. FIGURE 1(A) shows a model of what hardened cement paste gel might look like based on the assumption that gel particles are spherical. The solid dots represent gel particles, and the spaces bedween them are the gel pores; the larger spaces represent the residue of the originally water-filled space, i.e. the capillary pores. If the denser parts of the model were shown realistically, they would be opaque masses, because gel porosity is about 26% which, for spheres, requires a packing like closely stacked cannon balls.

There is little evidence that gel particles are spherical. As seen with the electron microscope, cement gel consists mostly of fibrous particles with straight edges. Bundles of such fibres seem to form a cross-linked network, containing some more or less amorphous interstitial material. A model based on fibrous or platy structure is shown in FIGURE 1 (B).

Cement paste is intrinsically porous and permeable. The densest possible completely hydrated cement paste has a porosity of 26%. The porosity of paste as a whole is usually greater and it depends on the original water content and on the extent to which space has become filled with hydration products. It depends, therefore, on the original water-cement ratio and on the conditions of curing.

2-3 MECHANISMS OF FREEZE-THAW DETERIORATION

While the mechanism of the several destructive processes in such a heterogeneous material as concrete are complicated and not completely understood, they have been rather satisfactorily detailed by some investigators (A.R. Collins 1944, T.C. Powers 1945, 1949, 1956).

2-3-1 The Taber-Collins Hypothesis

S. Taber (1929) has explained how frost upheavals occur in soils, due to macroscopic ice segregation. When free water turns into ice in the larger voids and cavities, the capillary water is drawn from the unfrozen soil, and ice lenses are developed. If the possibility of continued capillary suction of water from the ground-water zone exists, the ice lenses will grow, and the result will be frost upheavals.

The formation of ice lenses has been used by Collins (1944) as the explanation of the deterioration of low quality concrete with access to moisture from the surroundings. He concluded from observations in the field and experiments in the laboratory that frost damage in concrete occurs by macroscopic segregation of ice into layers in the concrete and that the layers exert pressure by growth in a direction opposite to the flow of heat.

The Taber-Collins hypothesis is an application of Taber's theory for frost heaving in soils to concrete. Although Taber's theory is highly satisfactory for explaining frost heaving in soils, there are several reasons for believing that it should not be applied to concrete or at least not to concrete frozen under usual conditions (T.C. Powers 1945). Evidence against the Taber-Collins hypothesis includes:

(1) In laboratory tests, the lower the rate of freezing, the smaller the destructive effect, whereas the Taber-Collins hypothesis requires the opposite result.

(2) Concrete must freeze as a "closed system" whereas segregation of ice can occur only in "open systems".

(3) Consideration of permeability and resistance to expansion makes the formation of ice lenses less favorable.

P. Nerenst (1960) pointed out that, "In the initial stages of hydration concrete will be affected by frost action in exactly the same way as soil which is subject to frost heaving. When freezing takes place at later ages, a hydraulic pressure will develop in the voids of the concrete and cracking will result."

T.C. Powers (1956) concluded that macroscopic ice segregation will only take place in mature concrete when the water-cement ratio is above 0.9 by weight and under special climatic conditions while it is likely to occur in any concrete during the early stages of hydration.

2-3-2 Hydraulic Pressure Hypothesis

As mentioned in a previous section of this report, two types of pores exist in cement gel namely; gel pores and capillary pores. The gel pores are so small that water does not freeze in them at temperatures likely to be encountered by concrete in the field. There exists then a system of capillary cavities, most of which are surrounded by and separated from each other by an unfrozen gel system of low permeability.

When water in a saturated capillary pore freezes, the expansion produced in the ice-water system requires a dilation of the cavity of some 9 per cent of the volume of frozen water, or the forcing of that

volume of water out of the cavity into the surrounding paste, or a combination of both.

The magnitude of the hydraulic pressure required to effect the excess volume of water resulting from progressive freezing depends on:

(1) Distance from the capillary cavity to a point of pressure relief.

(2) Rate of ice formation,

(3) Permeability of the intervening material, and

(4) Any elastic accommodation of the material around the cavity.

If the hydraulic pressure developed is in excess of the strength of the cement paste, then failure can be expected. Of the four factors determining the magnitude of the pressure developed, only the first may be readily modified to the necessary degree to prevent damage in severe exposures.

On this basis the concept of critical half thickness was developed by T.C. Powers (1945). For the air-entrained paste the critical half thickness is equal to the maximum half-thickness between the air voids. The walls of the air voids represent points of pressure relief.

By the use of a suitable air-entraining agent, a very large number of air voids may be incorporated in the cement paste. These air voids reduce the critical thickness of the layers of paste as the wall of the air bubbles serve as a point of pressure relief. In this way the resistance of cement paste to freezing and thawing cycles can be greatly increased.

T.C. Powers (1949) states, "Microscopic examination of concrete containing the amount of entrained air required to produce high resistance to the freezing and thawing test reveals that the bubbles

are very close together in the paste." Indications are that the computed spacing factor, based on air content and specific surface of air voids should be less than about 0.01 inches. More recently (A.C.I. Committee 201, 1962) stated, "If enough entrained air voids are present so that no capillary void is more than about 0.007 of an inch from an entrained air void, experience has shown that disruptive hydraulic pressures will not develop in the paste fraction of normal concrete."

The hydraulic pressure concept can be applied to the aggregate fraction of concrete as well as to the cement paste fraction. Hydraulic pressure in aggregates has been considered in detail by G. Verbeck and R. Landgren (1960). The major aspects and the important factors involved in the physical mechanisms applied to concrete aggregate are as follows:

(1) The time required for an aggregate particle to become critically saturated when in concrete exposed to water as influenced by:

(a) Pore size and porosity of aggregate

(b) Thickness and permeability of protective mortar cover

(2) The various phenomena in the freezing of fully saturated aggregate demonstrating:

(a) Elastic accommodation by aggregate

(b) Critical size of aggregate (internal hydraulic pressures)

(c) Influence of confining mortar (external expulsion distance and external hydraulic pressures)

(d) The influence of various factors modifying these effects of freezing, that is, soluble materials, degree of saturation and freezing point depression in fine aggregate pores.

2-3-3 MICROSCOPIC ICE SEGREGATION

The theory of segregation of ice on a microscopic scale within the cavities of the hardened paste has been presented by Powers and Helmuth (1953).

Research work done in the laboratories of the Portland Cement Association experimentally confirmed the hydraulic pressure theory but at the same time this theory did not account for all the phenomena observed. In particular it did not account for shrinkage that accompanies freezing when air voids are present nor for certain responses to change in rate of cooling. To account for these phenomena, consideration must be given to what may happen after the water in the capillary cavities becomes frozen. (Remember that water cannot freeze in the gel pores). If the gel is saturated, the gel water has the same free energy as that of ordinary water in bulk. If now the temperature drops below the temperature at which the water in the capillary cavities becomes frozen, a free energy difference will develop between the gel water and the ice in the capillary cavities. The gel water has a higher free energy, enabling it to move into the cavities and cause ice crystals to grow and enlarge the cavities. From the same considerations of thermodynamics it can be stated that while the gel water is diffusing to capillary cavities, it is diffusing also to the air voids.

As the ice crystals draw water from the gel by a diffusion process, the gel will tend to shrink, and osmotic pressure will be produced by water tending to enter partly frozen capillary cavities. The diffusion of water from gel to the capillary cavities will tend to cause dilation of the capillary cavities.

For cement pastes without entrained air the overall effect is dilation of the cement paste. Paste containing sufficient amounts of well distributed air bubbles will permit this formation of ice without dilating, and as water is drawn from the gel, the overall effect is shrinkage of the cement paste.

As the amount of segregating ice depends upon a rather slow diffusion process, the length of the freezing period has an important influence upon the observed changes in length. This is in contrast to the hydraulic pressure, where the rate of cooling is the most important variable of the freezing conditions.

2-4 APPLICATION OF HYPOTHESIS

The length of the freezing period, the rate of temperature drop and the lowest temperature reached all have an important influence upon the type of pressure producing mechanism applicable, that is, the relative proportions due to the hydraulic pressure mechanism and the microscopic ice segregation mechanism.

According to Powers and Helmuth (1953), at the rates of cooling normally used in laboratory freezing and thawing tests, most of the expansion of average non-air-entrained concrete is due to hydraulic pressure. Concrete in the field cools more slowly, and low temperatures may be maintained for many hours or days. If the paste is not protected with entrained air, it is liable to be damaged by both mechanisms: first by the hydraulic pressure and then by growth of the ice bodies. The lower the temperature the more severe the final effect.

With air-entrained concrete the role played by hydraulic pressure will depend upon the degree to which the paste is protected by the air

voids. If the air voids are close together, and if the rate of cooling is not excessive, hydraulic pressure is exceedingly transitory, and diffusion to the air voids dominates the process almost immediately. If the air voids are too far apart for adequate protection of the paste, hydraulic pressure may play a more prominent role. The influence of the spacing factor is very important.

2-5 LABORATORY TESTING OF FREEZE-THAW DURABILITY

The evaluation and prediction of durability is a major problem yet to be adequately solved. The development of accelerated laboratory methods for the evaluation of durability has received much attention since the methods developed attempt to simulate in an accelerated fashion the deteriorating influences to be found in service.

The prediction of field performance based on the present empirical methods of laboratory evaluation poses at least three major considerations. There must first exist some suitable method of evaluating the progress of deterioration. Secondly, the selection of the proper exposure conditions (especially with respect to cooling rate) and the ways in which these are to be incorporated in a laboratory test have not as yet been resolved. At present, the ASTM has four tentative procedures for testing for durability under freeze-thaw conditions. Finally it must be possible to relate the performance of the material in the test with that to be expected in the field.

The four ASTM methods of evaluating the freeze-thaw durability of concrete in the laboratory are:

(1) Tentative Method of Test for Resistance of Concrete Specimens to Rapid Freezing and Thawing in Water (C290-61T).

(2) Tentative Method of Test for Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water (C291-61T).

(3) Tentative Method of Test for Resistance of Concrete Specimens to Slow Freezing and Thawing in Water or Brine (C292-61T).

(4) Tentative Method of Test for Resistance of Concrete Specimens to Slow Freezing in Air and Thawing in Water (C310-61T).

The rapid freezing and thawing in water method was used in this investigation. The Highway Research Board Special Report No. 47 (1959) comments as follows on this method.

(1) The methods involving freezing and thawing in water are more severe than those involving freezing in air and thawing in water.

(2) The rapid freezing and thawing in water method has the advantage of producing a given number of cycles in a small fraction of the time required for the slow methods.

(3) Of the several procedures, the rapid freezing and thawing in water method has the advantage of great severity and a uniformly reproducible degree of saturation during exposure. It distinguishes quickly and decisively between very good concrete and concrete which is less durable either because of insufficient air or because of poor coarse aggregate. On the other hand, the severity of this method may be so great, that no differentiation will be provided between mixes of low durability.

(4) Within-laboratory uniformity of durability factors is quite good for the rapid freezing and thawing in water test method.

Reproducibility may be excellent for poor concretes because of their very rapid failure, but may be relatively less for the concrete which produces intermediate durability. Poorer reproducibility of results in the middle range of durability appears to be a natural and inescapable characteristic of results of this kind of testing.

(5) To insure the usefulness of laboratory freezing and thawing tests, additional research is needed on the degree to which they indicate field performance. An important consideration is that weathering conditions in the field range from highly destructive to completely innocuous and that differences shown by laboratory tests will in many cases have no practical significance. It seems likely that the ability of a concrete to withstand a severe laboratory freezing and thawing test is evidence of a high degree of durability. Failure provides a warning that can aid in evaluating the need for altering the characteristics of the concrete.

T. C. Powers (1955) raised questions about current test methods. He maintained that rapid freezing in the laboratory may destroy concrete that is immune to frost under natural conditions. Some laboratory test procedures introduce conditions fundamentally different from the most prevalent field conditions. The two most important discrepancies pertain to (1) rate of cooling and (2) length of continuous exposure to moisture. Since the actual field exposure conditions are not given due consideration, the laboratory test tends to give a distorted picture of relative frost resistance, usually it gives an over-load test, rather than an accelerated

natural process. In order to overcome this, Powers proposed a new procedure that takes category of field exposure into account and uses the period of immunity to frost attack as the primary measure of frost resistance.

2-6 MICROSCOPIC ANALYSIS

Optical measurements made on polished sections of concrete may be made to determine cement content and air void parameters in hardened concrete. This may be accomplished by one of three general procedures, namely:

(1) Areal Traverse Method

(2) Point Count Method

(3) Linear Traverse Method

The Areal Traverse Method of determining air void parameters involves the measurement of the area occupied by sections of air voids on plane surfaces of concrete. The air content is simply the percentage this area is of the total concrete area used. The method was employed first by Verbeck (1947), who measured the area of the void sections in camera lucida drawings of the finely ground surfaces. Photographs also may be used for this purpose.

The Point Count Method was developed for mineralogic analysis of rock, but can also be used to determine the air void content of concrete. The method is as accurate as other microscopical methods of analysis and the air content can be determined more rapidly than by the areal or linear traverse method. It is based on Felix Chayes analysis (Polivka et al 1958) that the frequency with which a given constituent occurs at a given number of equally spaced points along a random line in a random section is a

direct measure of the relative volume of that constituent in the solid, provided that the sampling is adequate and regardless of whether or not the constituents are randomly distributed. The truth of this statement is immediately evident because the probability that a given constituent will occur at a random point in a solid is precisely the ratio of the volume of that constituent to the total volume of that solid. The procedure involves examination of a finely ground surface or thin section under a microscope at regularly spaced points. This method can be used to determine the cement content and also the air content of hardened concrete. If during the traverse the total number of air voids intersected are recorded, then the air void parameters of specific surface and spacing factor can also be determined. This modification of test procedure is referred to as the Modified Point Count Method in A.S.T.M. designation C457-60T.

The linear traverse method is based upon procedures described by Rosiwal in 1898 for determining the volume of mineral in rock. He showed that the volume per cent of the constituents of a solid could be obtained from measurements along a random line through the solid. Lengths of segments or chords intercepted are summed separately for each constituent. The proportion for any one constituent then is the summation for that constituent divided by the summation of all constituents.

In practice the random line is obtained by first cutting a random plane through the solid, then traversing the surface along a series of straight lines, preferably parallel and uniformly spaced. Intercepts of constituents are measured along these traverses.

Using the linear traverse method in accordance with A.S.T.M. designation C457-60T, the air void parameters may be obtained of polished sections of concrete. With measured values of the total traverse length of the solid concrete constituent and the total traverse length of the chord intercepts of the air voids, as well as the total number of air voids intersected in the entire traverse the following air void parameters may be calculated.

(1) Air void content

(2) Average chord intercept of the air void in inches

(3) Average number of air void sections intercepted per inch

(4) Specific Surface

(5) Spacing Factor

2-7 EFFECTS OF THE USE OF CALCIUM CHLORIDE AS AN ADMIXTURE ON HARDENED CONCRETE

2-7-1 Effect on Strength

Calcium chloride is the most common accelerator used to hasten the strength development of concrete. It is commonly used during cold weather to accelerate the set and strength gain so that the forms can be removed earlier and to make the concrete more resistant to freezing temperature during its early age.

W.H. Price (1949) concluded that for those concretes made and cured at 70° F., the very early strength development (up to 12 hours) was increased as the percentage of calcium chloride was increased up to 3 per cent. The 28-day strength of the concrete made at 70° F. and containing 3 per cent calcium chloride was about 2 per cent lower than that of the concrete containing no calcium chloride, and about 12 per cent lower than the

concrete containing 2 per cent calcium chloride. Other results indicated that as the placing temperature decreases, the percentage of calcium chloride must be increased for optimum results.

2-7-2 Effect on Freeze-Thaw Durability

Many tests have been made by the Bureau of Reclamation to determine the effect of calcium chloride on the resistance of concrete to freezing and thawing (J.J. Shideler 1952). Many air-entrained concretes have been tested at various ages and under different curing conditions. While these tests indicate that calcium chloride improves the durability of concrete tested at early ages, they almost invariably show that calcium chloride decreases durability at later ages. Therefore, at early ages, the accelerated strength gain as a result of the calcium chloride additive would appear to provide increased resistance to freeze-thaw durability, however at later ages where the effect of calcium chloride on strength is reduced, the resistance to freeze-thaw exposure is decreased.

2-7-3 Effect on Void Spacing and Pore Structure

In an attempt to explain the above, an investigation of the effects of calcium chloride on the void parameters of hardened concrete appeared to be a logical approach. Previous comments in this report have illustrated the dominant influence of the spacing factor on freeze-thaw durability. Consequently any relation between the additions of calcium chloride to concrete and the effect on air void parameters can be expected to influence its freeze-thaw durability.

The literature on this problem is very limited and to some extent is conflicting:

R.C. Mielenz et al (1957) states, "The addition of 1 per cent calcium chloride to air entrained concrete resulted in larger bubbles and a higher spacing factor. Since calcium chloride is generally used in cold weather, the cumulative adverse effects on bubble size and spacing factor may be increased appreciably with possible serious effects on freezing and thawing resistance." G.M. Bruere (1960) stated, "The characteristics of entrained bubbles are practically unaffected by either the presence of calcium chloride in pastes containing neutralized 'Vinsol Resin' or the order in which these agents are added to pastes."

CHAPTER III

TEST PROGRAM

3-1 GENERAL LAYOUT OF TESTING PROGRAM

The object of this program was to compare the freeze-thaw durability of concrete made using normal cement, high early strength cement, and normal cement plus calcium chloride as an accelerator. To accomplish this objective eighteen different concrete mixes were cast, cured and tested. The concrete properties determined in this investigation were the compressive strength of 3" by 6" concrete cylinders and the freeze-thaw durability of 3 1/2" by 4 1/2" by 16" beams. Microscopic examination of polished sections was made to determine the nature of the air-entrainment in the concrete.

For the mix designs, the following materials and conditions were kept constant:

(1) Fine and coarse aggregate

(2) Air content for air entrained mixes

(3) Curing Conditions

(4) Consistency

(5) Compaction

(6) Mixing time and mixing procedure.

The variable aspects of this investigation were:

(1) Cement - type (a) normal (b) high early strength

- content - 400, 550, 700 pounds per cubic yard.

(2) Calcium chloride admixture 0, 1, 2, 3 % by weight of cement

(3) Air content - non-air-entrained mixes

- air-entrained mixes - Darex as air-entraining agent.

The mixes may be summarized as follows:

Mix 1 - (N-400-0)Type 1 cement, 400 lbs./cu.yd., non-air-entrained and no admixture.

Mix 2 - (N-550-0) Type 1 cement, 550 lbs./cu.yd., non-air-entrained and no admixture.

Mix 3 - (N-700-0) Type 1 cement, 700 lbs./cu.yd., non-air-entrained and no admixture.

Mix 4 - (6N-400-0) same as Mix 1 except 6% air-entrained

Mix 5 - (6N-550-0) same as Mix 2 except 6% air-entrained

Mix 6 - (6N-700-0) same as Mix 3 except 6% air-entrained

Mix 7 - (6N-400-1) same as Mix 4 except 1% calcium chloride added

Mix 8 - (6N-550-1) same as Mix 5 except 1% calcium chloride added

Mix 9 - (6N-700-1) same as Mix 6 except 1% calcium chloride added

Mix 10- (6N-400-2) same as Mix 4 except 2% calcium chloride added

Mix 11- (6N-550-2) same as Mix 5 except 2% calcium chloride added

Mix 12- (6N-700-2) same as Mix 6 except 2% calcium chloride added

Mix 13- (6N-400-3) same as Mix 4 except 3% calcium chloride added

Mix 14- (6N-550-3) same as Mix 5 except 3% calcium chloride added

Mix 15- (6N-700-3) same as Mix 6 except 3% calcium chloride added

Mix 16- (6HE-400-0) Type 3 cement, 400 lbs./cu.yd., 6% air-entrained

Mix 17- (6HE-550-0) Type 3 cement, 550 lbs./cu.yd., 6% air-entrained

Mix 18- (6HE-700-0) Type 3 cement, 700 lbs./cu.yd., 6% air-entrained

The test specimens from each mix were coded as shown in the previous brackets. This code may be read as shown in the following example. For 6N-550-2;

6 - 6% apparent air content
N - Normal portland cement
550 - 550 lbs. of cement per cubic yard
2 - 2% calcium chloride added by weight of cement

For each mix, 20 cylinders and 3 beams were cast and cured. The strength testing was carried out mainly as a control measure, however the relationships between compressive strength, age and percentage of calcium chloride are discussed. Strength testing was carried out at 7, 14, and 28 days curing time and in addition samples were fabricated to determine the strengths after 3 months and 6 months curing. These latter results are not available for inclusion in this report due to the time factor involved.

Two concrete beams were selected from each mix and subjected to freeze-thaw testing at an age of 14 days as outlined in A.S.T.M. designation C290-61T, "Resistance of Concrete Specimens to Rapid Freezing and Thawing in Water." The rate of deterioration was measured by the Sonic Modulus Method, A.S.T.M. designation C215-61T.

The remaining concrete beam from each mix was sectioned with the diamond saw and one section from near the center of the beam was selected and polished on a cast iron lapping wheel. The polished surface was subjected to a microscopic examination for air-void content by the Linear Traverse Method as outlined in A.S.T.M. designation C457-62T.

3-2 MATERIALS

The materials in this investigation were all obtained from the local

TABLE I

PHYSICAL PROPERTIES OF AGGREGATE

PHYSICAL PROPERTY	AGGREGATE	
	COARSE	FINE
Specific gravity - Bulk	2.55	2.55
- Apparent	2.64	2.64
- Saturated Surface Dry	2.58	2.59
Absorption - %	1.31	1.23
Dry Rodded Unit Weight - lbs./cu. ft.	96.0	---
Color Test (Alternate Procedure B)		#1

TABLE II

SIEVE ANALYSIS OF AGGREGATE

SIEVE SIZE	WT. RETAINED	% RETAINED	CUM. % RET.	A.S.T.M. SPEC.
Coarse aggregate				
1	0	0	0	
3/4	36.1	0.9	0.9	
1/2	2854.2	68.3	69.2	
3/8	803.4	19.2	88.4	
1/4	423.1	10.2	98.6	
-1/4	57.5	1.4	100.0	
Fine aggregate				
4	22.6	3.20	3.20	0-5
8	95.5	13.70	16.90	
16	106.2	15.10	32.00	20-55
30	81.6	11.70	43.70	
50	240.8	34.50	78.20	70-90
100	116.5	16.70	94.90	90-98
PAN	35.5	5.10	100.00	
FINENESS MODULUS = 2.69				

TABLE III

PETROGRAPHIC ANALYSIS OF COARSE AGGREGATE

QUARTZITE	GRANITES	LOCAL BEDROCK sandstone clay-iron-nod. cherts	LIMESTONE dolomites	TOTAL PIECES
1157	212	219	49	1637
70.6%	13.0%	13.4%	3.0%	

TABLE IV

PHYSICAL PROPERTIES OF CEMENT

PHYSICAL PROPERTY	CEMENT	
	NORMAL	HIGH EARLY
TIME OF SET (VICAT APPARATUS)		
initial hrs. - min.	3 : 54	4 : 25
final hrs. - min.	6 : 10	5 : 25
WATER FOR NORMAL CONSISTENCY - %	26.0	34.4
TENSILE STRENGTH - p.s.i.		
1 day	---	410
3 day	505	655
7 day	600	750
28 day	600	---
COMPRESSIVE STRENGTH - p.s.i.		
1 day	1140	1480
3 day	2180	3590
7 day	3125	4550
28 day	4080	5820

producers in Edmonton. The cements used, normal portland cement and high early strength portland cement, were manufactured by Inland Cement Company Limited.

The fine and coarse aggregates were obtained from Dales Brothers Limited. These aggregates were from their Onoway source.

The admixtures used in this investigation were Darex, as the air entraining agent and calcium chloride. The calcium chloride used was type 1 regular flake (minimum 77% available soluble calcium chloride).

3-2-1 Aggregate Tests

The following tests on the fine and coarse aggregate were carried out in accordance with the A.S.T.M. methods indicated:

(1) Specific Gravity and Absorption of Coarse Aggregate, A.S.T.M. designation C127-42.

(2) Unit Weight of Aggregate, A.S.T.M. designation C29-55T.

(3) Sieve Analysis of Fine and Coarse Aggregate, A.S.T.M. designation C136-46.

(4) Specific Gravity and Absorption of Fine Aggregate, A.S.T.M. designation C128-57.

(5) Organic Impurities in Sands for Concrete, A.S.T.M. designation C40-56T.

The physical properties of the aggregates are summarized in TABLE I and TABLE II. A petrographic analysis of the coarse aggregate was performed on the basis of a pebble count. The results indicate a glacial gravel predominately composed of quartzite particles. These results are shown in TABLE III.

3-2-2 Cements Tests

The cement tests were carried out in accordance with the Canadian Standards Association Specification A5-1961. The results are summarized in TABLE IV. The values for tensile strength and compressive strength presented are the average of 3 specimens.

3-3 MIX DESIGN

The mix designs in this investigation were proportioned in accordance with ACI 613-54, Recommended Practice for Selecting Proportions for Concrete. The detailed computations are contained in Appendix C of this report. TABLES V, VI, and VII summarize the proportions of materials used.

3-4 LABORATORY EQUIPMENT

A considerable amount of laboratory equipment was required to mix, cast, cure and test the specimens for this investigation. Although the selection of the various equipment was governed by the type available, the equipment used was found to be very satisfactory. The following is a brief description of the various equipment used.

1. LABORATORY CONCRETE MIXER (Plate 1)

The laboratory concrete mixer used in this investigation was a "kwik Mix" model. The mixer was a 3 1/2 cubic foot tilting drum type powered by a 1 1/2 H.P., 220 volt, 3 phase induction motor. The speed of the mixer was 25 revolutions per minute.

2. VIBRATOR (Plate 1)

All mixes in this investigation were compacted by means of external vibration. The vibrator used was made by Syntron Electric Vibrators

TABLE V

MIX DESIGN PROPORTIONS - SAT. SURF. DRY BASIS

NO.	MIX	DATE CAST	DESIGN MIX PROPORTIONS PER CUBIC YARD (SAT. SURFACE DRY BASIS)					
			CEMENT lbs.	FINE AGG. lbs.	COARSE AGG. lbs.	WATER lbs.	ADMIXTURE Darex ml.	ADMIXTURE $CaCl_2$ lbs.
1	N-400-0	15/11/62	400	1492	1605	325		
2	N-550-0	15/11/62	550	1370	1605	325		
3	N-700-0	15/11/62	700	1250	1605	325		
4	6N-400-0	16/11/62	400	1410	1605	288	114	
5	6N-550-0	16/11/62	550	1290	1605	288	157	
6	6N-700-0	16/11/62	700	1170	1605	288	200	
7	6N-400-1	13/12/62	400	1410	1605	288	114	4.0
8	6N-550-1	13/12/62	550	1290	1605	288	157	5.5
9	6N-700-1	13/12/62	700	1170	1605	288	200	7.0
10	6N-400-2	14/12/62	400	1410	1605	288	114	8.0
11	6N-550-2	14/12/62	550	1290	1605	288	157	11.0
12	6N-700-2	14/12/62	700	1170	1605	288	200	14.0
13	6N-400-3	14/1/63	400	1410	1605	288	114	12.0
14	6N-550-3	14/1/63	550	1290	1605	288	157	16.5
15	6N-700-3	14/1/63	700	1170	1605	288	200	21.0
16	6HE-400-0	15/1/63	400	1410	1605	288	228	
17	6HE-550-0	15/1/63	550	1290	1605	288	314	
18	6HE-700-0	15/1/63	700	1170	1605	288	400	

TABLE VI

MIX DESIGN PROPORTIONS AS CAST - WET WEIGHTS

NO.	MIX	DESIGN MIX PROPORTIONS AS CAST (WET WEIGHTS)						ACTUAL WATER lbs.	W/C	SLUMP inch.	APPARENT AIR CONT. Pressure Meter
		CEMENT lbs.	COARSE AGG. lbs.	FINE AGG. lbs.	WATER lbs.	ADMIXTURE Darex ml.	ADMIXTURE $CaCl_2$				
1	N-400-0	29.6	119.0	115.0	19.6			28.27	.955	3 1/4	0.9
2	N-550-0	40.7	119.0	105.5	20.0			25.41	.626	3	1.4
3	N-700-0	51.8	119.0	96.6	20.3			24.86	.482	3 1/4	1.3
4	6N-400-0	29.6	119.0	108.5	17.1	8.5		21.82	.738	3	6.0
5	6N-550-0	40.7	119.0	99.5	17.5	11.6		21.74	.534	2 3/4	5.7
6	6N-700-0	51.8	119.0	90.2	17.9	14.8		21.64	.418	3	6.0
7	6N-400-1	26.6	106.5	96.3	17.0	7.6	.266	20.35	.765	2 3/4	5.7
8	6N-550-1	36.6	106.5	88.2	17.3	10.5	.366	20.96	.572	3	5.7
9	6N-700-1	46.6	106.5	80.0	17.4	13.3	.466	20.96	.450	3 1/4	5.6
10	6N-400-2	26.6	106.5	96.3	17.0	7.6	.532	19.67	.740	3	5.9
11	6N-550-2	36.6	106.5	88.3	17.3	10.5	.732	19.54	.534	3 1/2	6.0
12	6N-700-2	46.6	106.5	80.0	17.4	13.3	.932	19.51	.418	3 1/2	5.5
13	6N-400-3	26.6	106.0	97.4	17.1	7.6	.798	21.43	.805	3	5.7
14	6N-550-3	36.6	106.0	97.0	17.4	10.5	1.098	21.80	.613	3	6.0
15	6N-700-3	46.6	106.0	96.8	17.7	13.3	1.398	22.09	.474	3 1/2	6.2
16	6HE-400-0	26.6	106.0	97.4	17.1	13.6		20.52	.772	3	5.7
17	6HE-550-0	36.6	106.0	97.0	17.4	21.0		21.40	.584	3	5.4
18	6HE-700-0	46.6	106.0	96.8	17.7	27.0		22.79	.489	3	5.8

TABLE VII

ABSOLUTE VOLUMES OF PROPORTIONS

NO.	MIX	ABSOLUTE VOLUMES OF PROPORTIONS CU. FT.							
		CEMENT	WATER	CEMENT + WATER	FINE AGG.	COARSE AGG.	APP. AIR Air Meter	TOTAL	PASTE CONTENT
1	N-400-0	.151	.454	.605	.685	.739	.024	2.053	.295
2	N-550-0	.208	.408	.616	.627	.739	.034	2.016	.306
3	N-700-0	.264	.398	.662	.573	.739	.032	2.006	.331
4	6N-400-0	.151	.350	.501	.646	.739	.126	2.012	.249
5	6N-550-0	.208	.348	.556	.591	.739	.120	2.006	.277
6	6N-700-0	.264	.347	.611	.536	.739	.126	2.012	.304
7	6N-400-1	.135	.327	.462	.582	.666	.108	1.818	.254
8	6N-550-1	.186	.337	.523	.533	.666	.108	1.830	.286
9	6N-700-1	.237	.337	.574	.483	.666	.106	1.829	.314
10	6N-400-2	.135	.315	.450	.582	.666	.111	1.809	.249
11	6N-550-2	.186	.313	.499	.533	.666	.113	1.811	.275
12	6N-700-2	.237	.313	.550	.483	.666	.104	1.803	.305
13	6N-400-3	.135	.344	.479	.582	.666	.108	1.835	.261
14	6N-550-3	.186	.350	.536	.533	.666	.113	1.848	.290
15	6N-700-0	.237	.355	.592	.483	.666	.117	1.858	.319
16	6HE-400-0	.135	.329	.464	.582	.666	.108	1.820	.255
17	6HE-550-0	.186	.343	.529	.533	.666	.103	1.831	.289
18	6HE-700-0	.237	.365	.602	.483	.666	.110	1.861	.323

(Model VP60) and distributed by Soil Test Laboratories. The vibrator had an adjustable vibration amplitude which was controlled by a variable resistor dial. A dial setting of 50 was selected and all specimens were cast in 2 separate layers with a period of vibration of 8 seconds per layer.

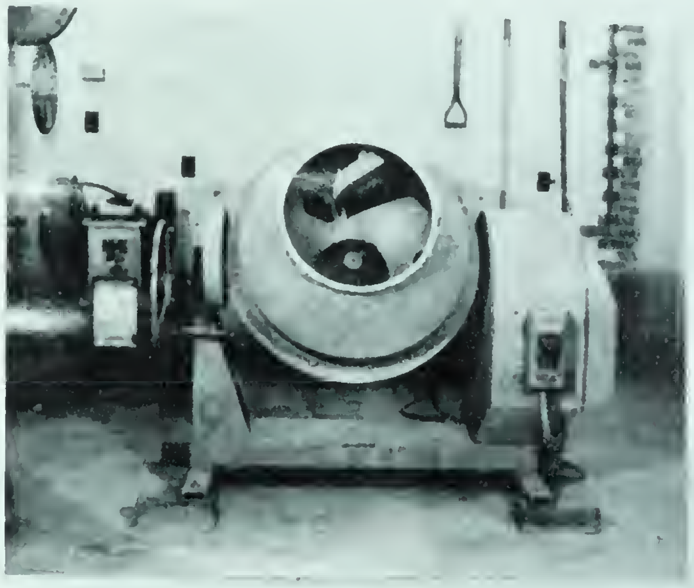
3. PRESSURE AIR METER (Plate 1)

The air meter used in this investigation was a Press-Ur-Meter manufactured by Concrete Specialties Co. of Spokane, Washington. This meter utilizes the principle of Boyles law. The action of the Press-Ur-Meter is to equalize the pressure of a known volume of air at a given initial pressure in the sealed air chamber with an unknown volume of air in the concrete contained in the air meter. The changes in barometric pressure will not affect the results as such pressures are balanced in both chambers. The volume of the base of this particular model was 0.250 cubic feet.

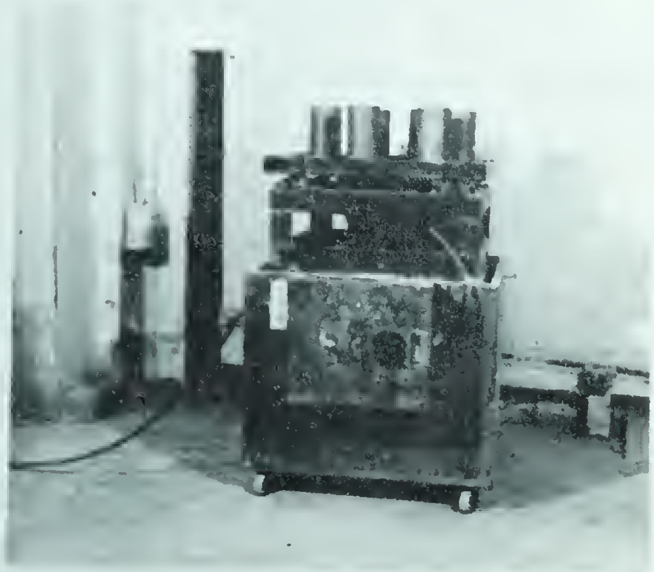
4. MOLDS (Plate 1)

The compressive strength specimens were fabricated in 3 inch diameter by 6 inch long cylindrical molds. These molds were made from stiff waxed cardboard with a cardboard bottom.

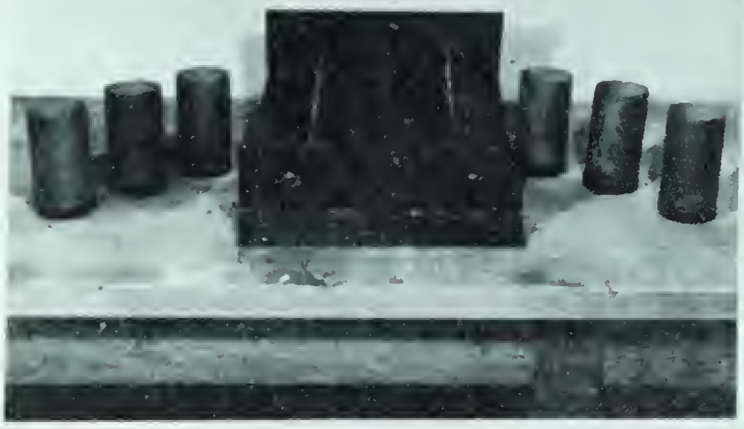
The beams for freeze thaw testing and also for microscopic analysis were fabricated in 3 1/2 by 4 1/2 by 16 inch molds. These molds were made of 1/4 inch steel plate and designed in such a manner so that they could be easily dismantled. Prior to placing any concrete in the beam molds, they were well lubricated with a light application of linseed oil.



LABORATORY CONCRETE MIXER



EXTERNAL VIBRATOR



MOLDS

AIR PRESSURE METER

PLATE I

5. SPECIMEN CURING TANK

It was desired to cure the specimens in a saturated lime solution at a temperature of 70 ±3° F. To obtain this curing condition a large galvanized iron tank was used of the dimensions 32 inches wide by 84 inches long and 14 inches deep. It was filled with water and slaked lime was added until a precipitate formed which indicated saturation of the solution. The specimen tank was located in the concrete laboratory which had a fairly constant temperature of 68 ± 3° F. However to maintain the temperature at 73 ± 3° F., a thermostatically controlled heating element was inserted in the tank and a small electrically driven pump was used to circulate the solution in the tank.

6. BALDWIN TESTING MACHINE (Plate 3)

The compression testing machine used for measurement of the compressive strength of the concrete cylinders was a Baldwin Southwark-Emery Testing machine. It was a hydraulic reaction type machine with a maximum capacity of 300,000 pounds. The load dial had 2 ranges; range one from 0 - 50,000 pounds and range two from 0 - 300,000 pounds. Range one was used in this investigation and the rate of loading was controlled by a built-in load pacer.

7. FREEZE-THAW EQUIPMENT (Plate 2)

The automatic freezing and thawing unit at the University of Alberta was set up by K.R. Lauer (1948) and later modified and improved by J.L. Jaspar (1950). For a complete and detailed description of the apparatus, references should be made to the above two theses.

A brief description of this apparatus is warranted. The apparatus

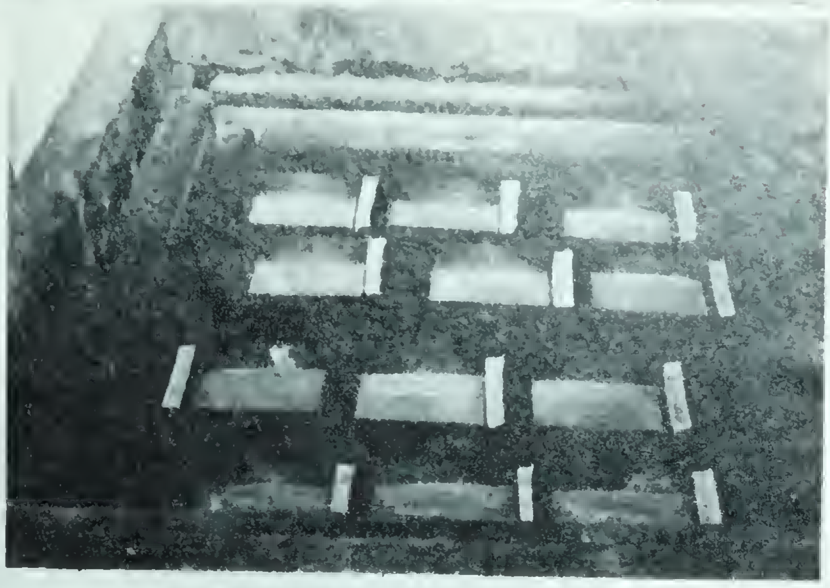
consists essentially of three tanks, a specimen tank, cold tank, and hot tank, with means for cooling the cold fluid, heating the hot fluid, and circulating the cold and hot fluids at the proper temperature in and out of the specimen tank during the specified intervals. A schematic diagram of the apparatus is shown in Figure 2.

This unit is capable of reducing the temperature of 12 - 3 1/2 by 4 1/2 by 16 inch concrete beams from 40° F. to 0° F. in one hour and in raising the temperature from 0° F. to 40° F. in the following hour. The apparatus is fully automatic and repeats each cycle every two hours and records the number of cycles on a tachometer. All valves and pumps are electrically operated and controlled by a circuit timer. The sequence of operation of the valves and pumps is given in TABLE VIII.

TABLE VIII

SEQUENCE OF OPERATION OF VALVES AND PUMPS

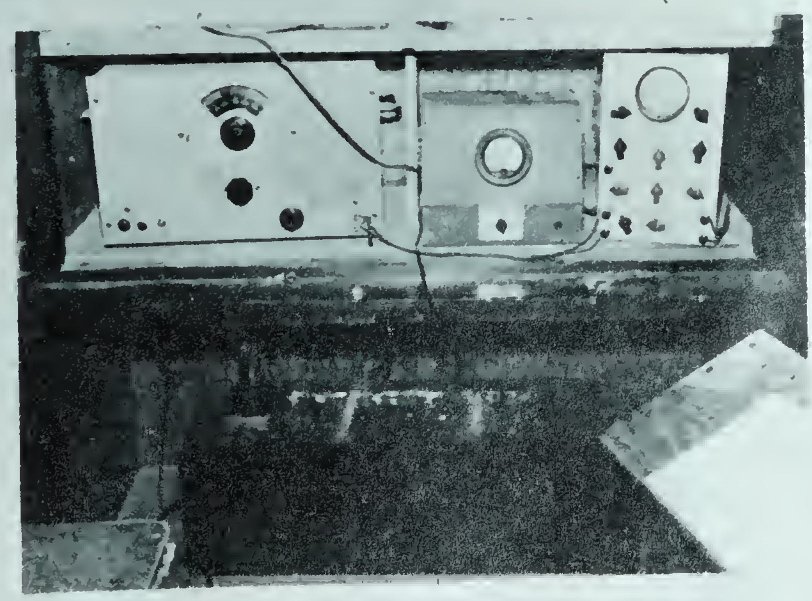
Elapsed Time Hr.	Min.	Sec.	Operation
0	0	0	Drain valve closes
0	0	30	Cold return valve opens
0	1	0	Cold pump starts
0	54	0	Cold pump stops
0	54	2	Drain valve opens
1	0	0	Drain valve closes
1	0	30	Hot return valve opens
1	1	0	Hot pump starts
1	54	0	Hot pump stops
1	54	2	Drain valve opens
2	0	0	Drain valve closes



SPECIMEN TANK

COLD TANK AND
REFRIGERATING UNIT

HOT TANK



SONIC MODULUS APPARATUS

PLATE 2

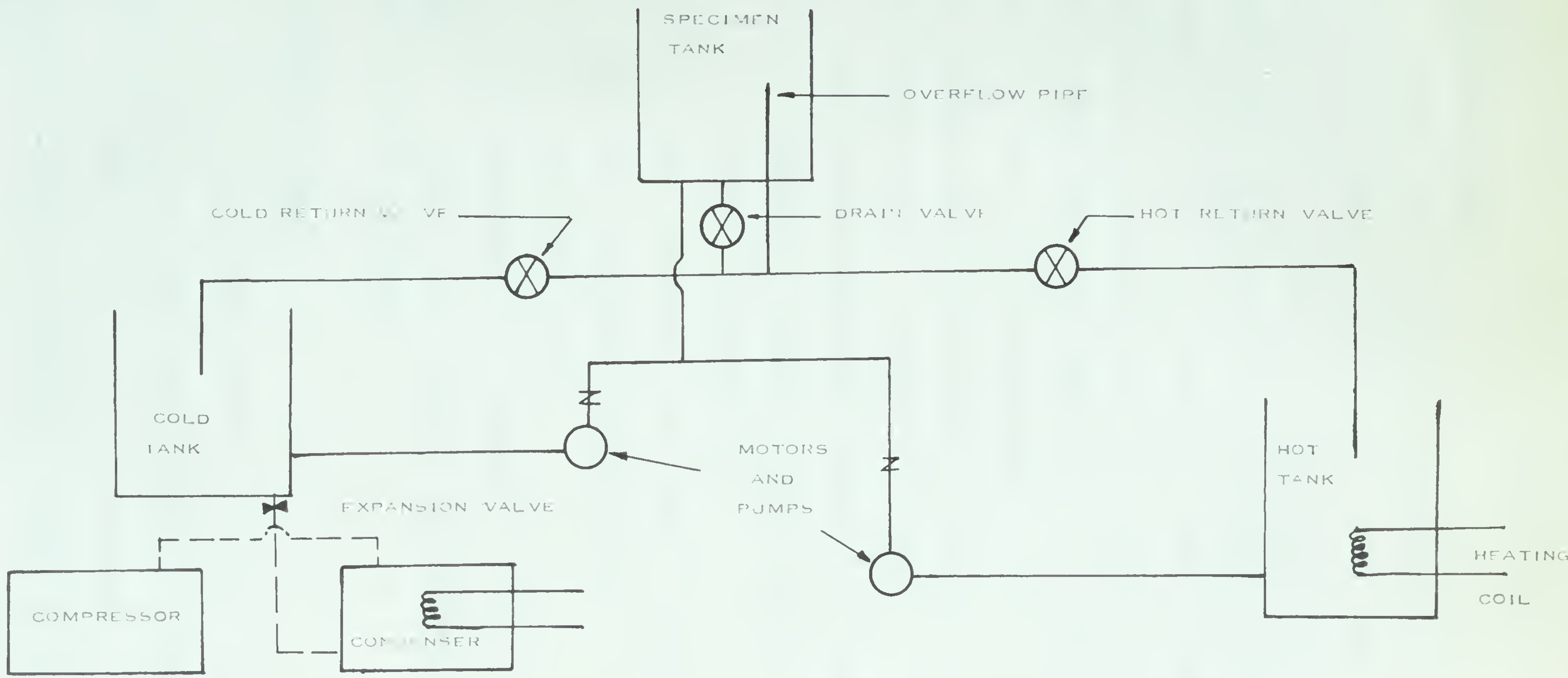


FIGURE 2 - SCHEMATIC DIAGRAM OF FREEZE-THAW APPARATUS

Temperature Records

Freeze thaw results are dependent on the rate of temperature change so that an accurate record was made of the temperature of the various cycles. A.S.T.M. Designation C 290 states that the temperature at the center of all specimens shall be alternately lowered to $0 \pm 3^\circ$ F. and raised to $40 \pm 3^\circ$ F. For this set of tests a dummy specimen was inserted which had three thermocouples in the specimen (see Figure 5). Also two other thermocouples were used; one in the water surrounding the specimen and one in the circulating refrigerating fluid (ethylene glycol). The dummy specimen was inserted prior to testing and also during the first set of tests in order to check the performance of the equipment.

These thermocouples were located as follows:

1. Near top of concrete beam at center of cross-section.
2. Center of concrete beam.
3. Near bottom of concrete beam at center of cross-section.
4. Water surrounding concrete beam.
5. Circulating fluid.

The temperatures were recorded by an automatic Browning temperature recorder. FIGURE 4 shows a typical time-temperature performance curve for this particular apparatus.

8. SONIC EQUIPMENT

The Sonic equipment was used to measure the progressive deterioration of the concrete specimens during freeze-thaw testing. This equipment consisted of a method of supporting the specimen so that it would vibrate in a prescribed mode of vibration, a method of vibrating the specimen in

that mode, and a means of measuring the frequency of vibration.

The specimen supports permitted the specimen to vibrate transversely in the free mode without restriction. The beam was supported at its nodal points (0,224 of its length from each end) by means of 1/8 inch triangular steel bars. These bars rested on a thick pad of sponge rubber.

The driving circuit consisted of a variable frequency audio oscillator and a driving unit. The oscillator was a Hewlett Packard No. 11012, calibrated to read within ± 2% of the true frequency over its range of use.

The pickup circuit consisted of a pickup unit, an amplifier, and a meter. A schematic diagram of this equipment is shown in FIGURE 3.

For a more detailed description of this equipment, the reader is referred to theses by K.R. Lauer (1948) and by J.L. Jasper (1950).

9. MICROSCOPIC ANALYSIS

The following equipment was used for the preparation of, and examination of, concrete samples by the method of microscopic analysis.

1. Concrete saw
2. Lapping wheel
3. Microscope
4. Traversing table

Concrete Saw (Plate 3)

The saw used for cutting the sections of concrete was made by Northland Lapidary Equipment Manufacturers of Edmonton. It used a stationary rotating 24 inch diameter diamond chipped blade. Specimens were clamped into a vice rack which fed the specimen automatically into

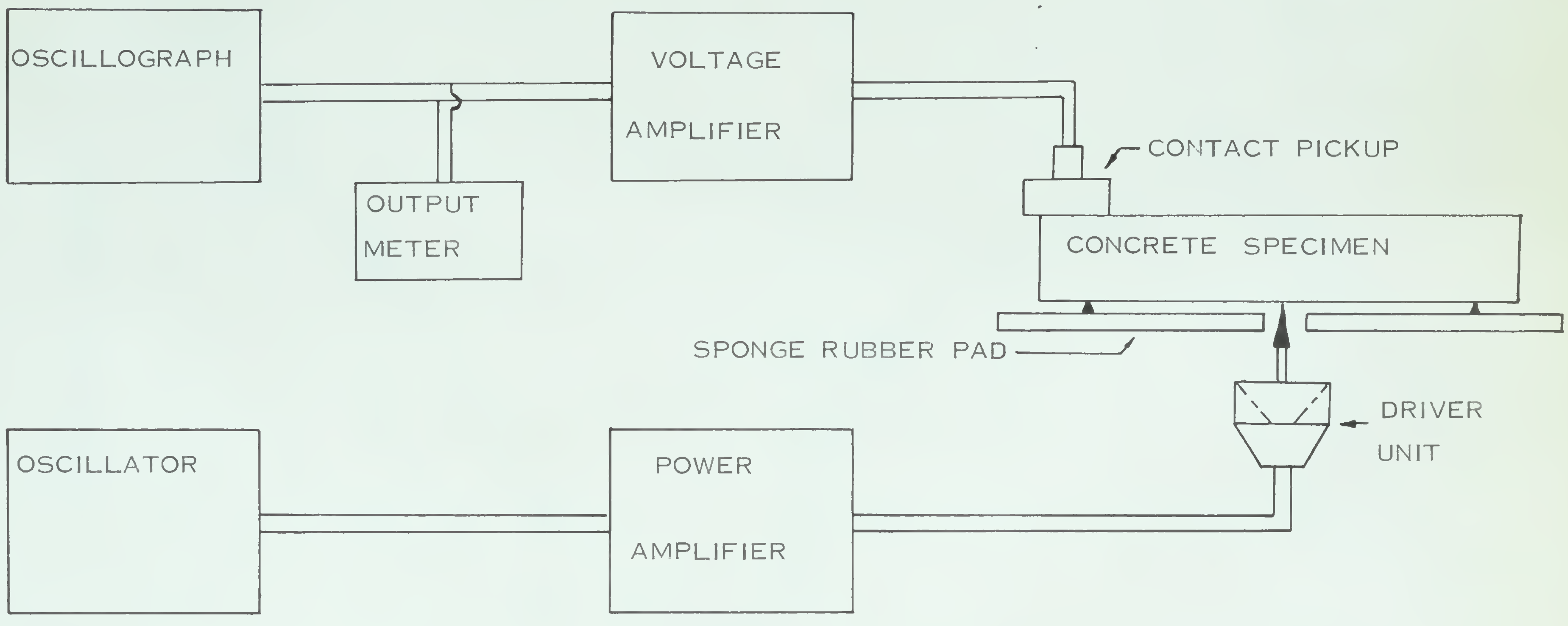


FIGURE 3 SCHEMATIC DIAGRAM OF SONIC APPARATUS

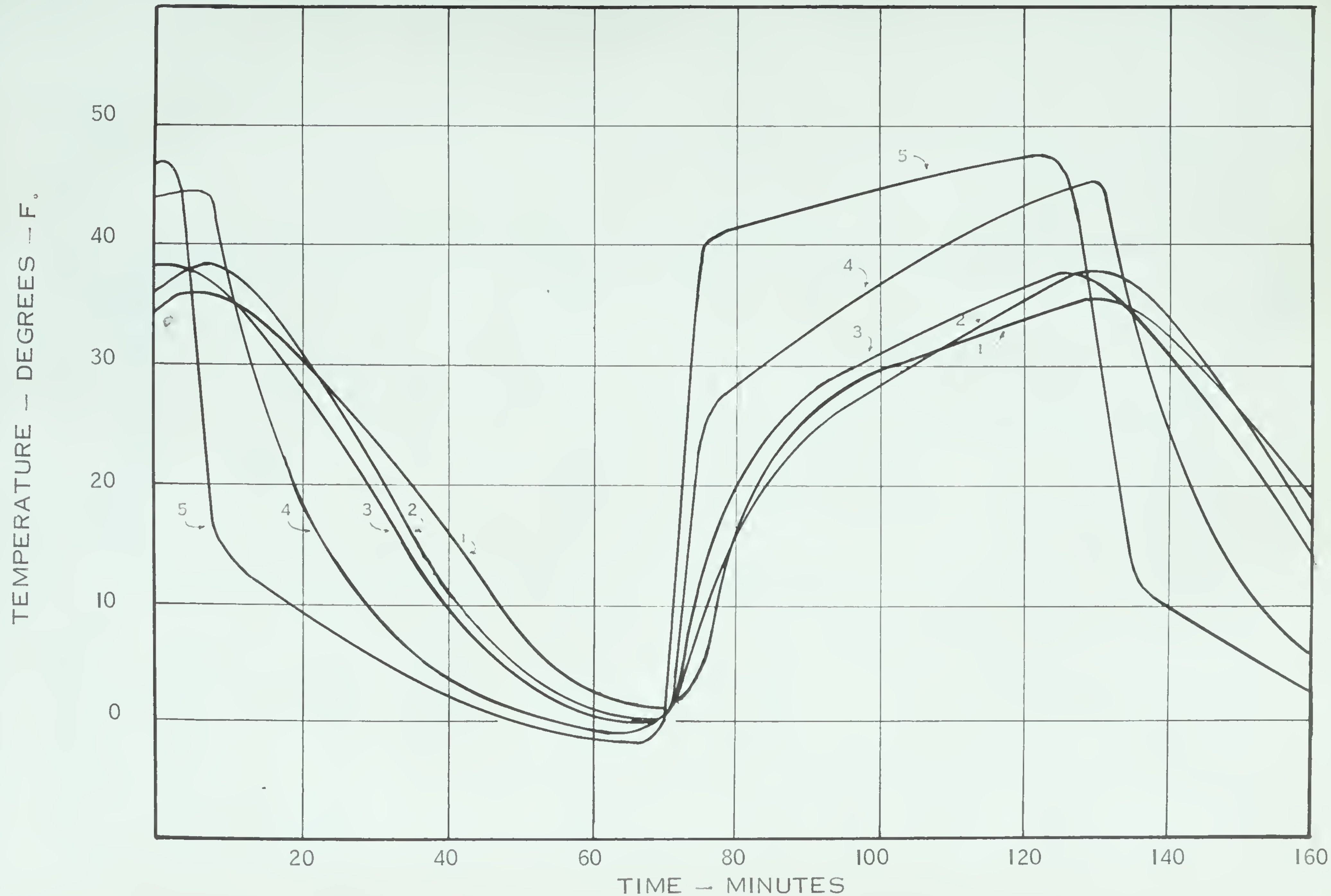


FIGURE 4 - TIME TEMPERATURE CURVE – RAPID WATER METHOD C290

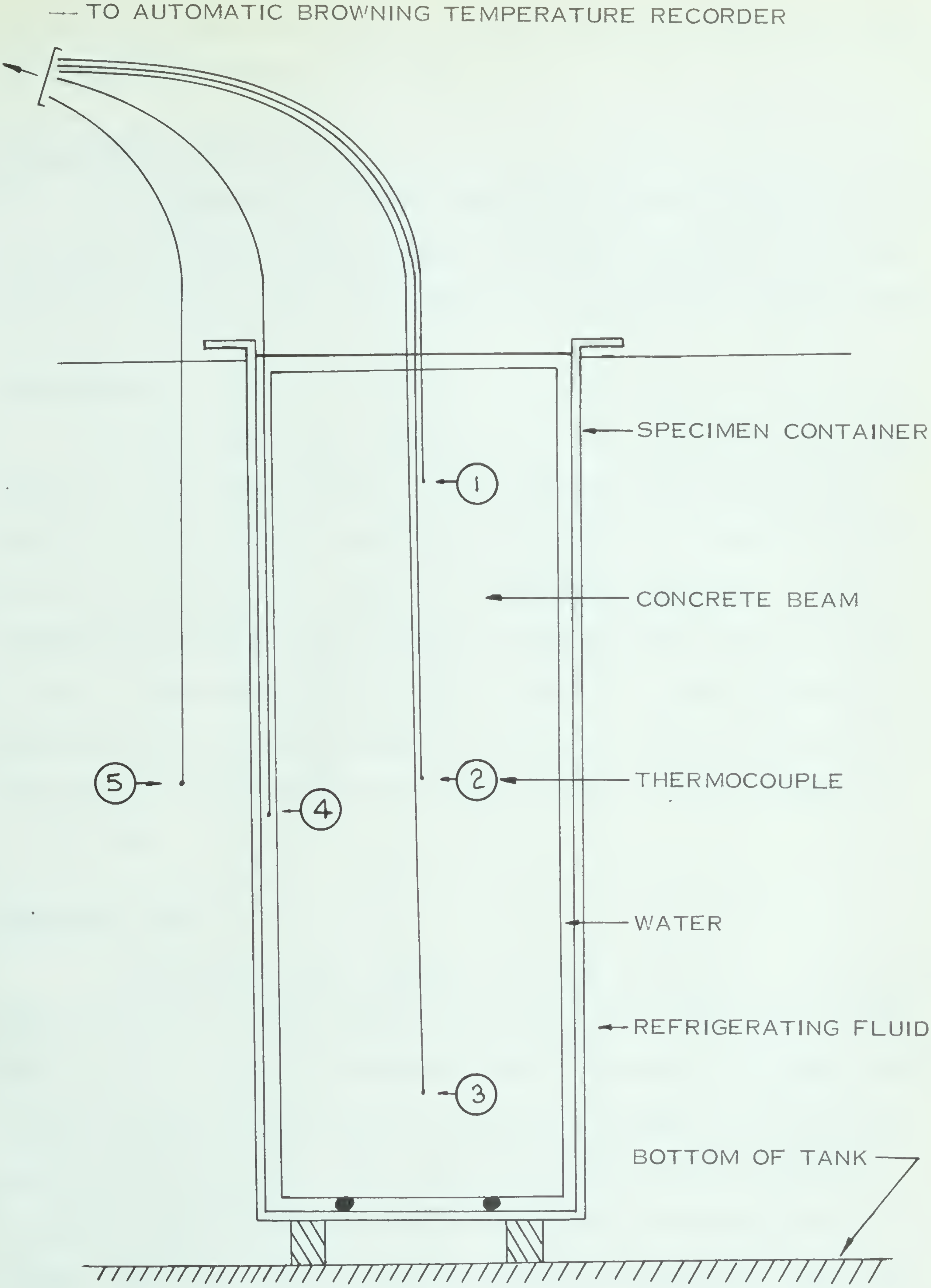


FIGURE 5 - SECTION – SHOWING POSITIONS OF THERMOCOUPLES IN DUMMY SPECIMEN

the saw. The rate of feed could also be controlled. This saw cut the specimen with one pass of the blade.

Lapping Wheel (Plate 3)

The preferred method for polishing the concrete sections was found to be with a cast iron lapping wheel. This unit consisted of a 20 inch diameter cast iron wheel, belt driven by a 1/4 horsepower electric motor.

Microscope

The microscope used in this project was a stereoscopic type manufactured by Carl Zeiss (Jena). It has adjustable magnification made possible by three sets of eyepieces of 5X, 10X, and 15X magnification as well as two objective lenses of 2X and 6X magnification. The 15X magnification eyepiece was selected with the 6X magnification objective to give a total magnification of 90X. A Bausch and Lomb illuminator was attached to the microscope stand and adjusted to throw a beam across the field at a low angle so that the shadows would facilitate recognition of the voids.

Traversing Table

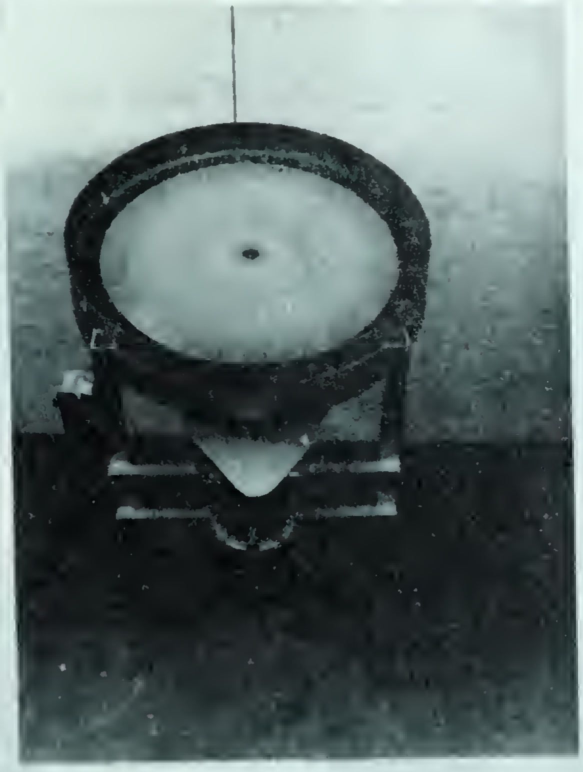
A photograph of this equipment is shown in Plate 4. The traversing table consisted of three principle parts; the base plate, main carriage and top plate. It was so constructed that a specimen of concrete placed on the top plate could be moved uniformly and smoothly in two mutually perpendicular directions. The main carriage moved along a leadscrew attached to the base plate and the total possible translation was 14 inches. The top 6 inch by 12 inch plate moved independently along the

top of the main carriage. It was operated by two handwheels. One handwheel caused horizontal movement parallel to the main lead screw which was recorded in units of 0.05 inches by a counter mounted on the right side of the top plate. The other handwheel was used for vertical movements at right angles to the main leadscrew and it moved the specimen 0.05 inches for each revolution. Each motion of the top plate had a total possible translation of 6 inches.

Power was supplied to the main carriage by a Singer Sewing machine motor which was mounted at the left end of the lead screw and controlled by a Singer Sewing motor controller. The rotation speed was variable up to a maximum of 20 revolutions per minute. The amount of translation was recorded by a revolution counter mounted at the right end of the screw. One revolution produced 0.05 inches of translation. The rotation counters attached to the main leadscrew and upper leadscrew are supplemented by an indicator such that the number of revolutions can be read to the nearest o.01 revolution (.0005 inches).

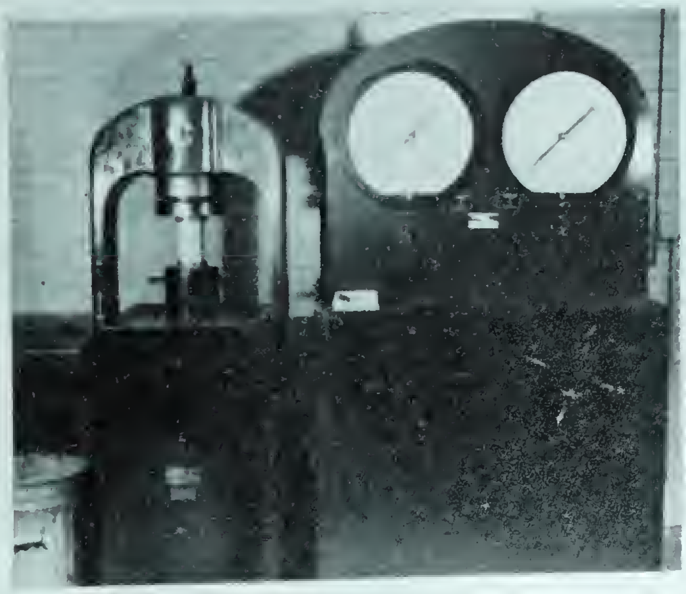
The base plate was 44 inches long and 12 inches wide and was bolted to the wall in order to prevent any movement or vibration during the analysis.

During the traverse, the main carriage and specimen moved laterally under the microscope. A movement of the top plate was a measure of the air voids while the movement of the main carriage was a measure of the solid components of the concrete. The number of air voids intersected during the traverse was recorded on an individual counter.



LAPPING WHEEL

CONCRETE SAW



BALDWIN TESTING MACHINE

PLATE 3

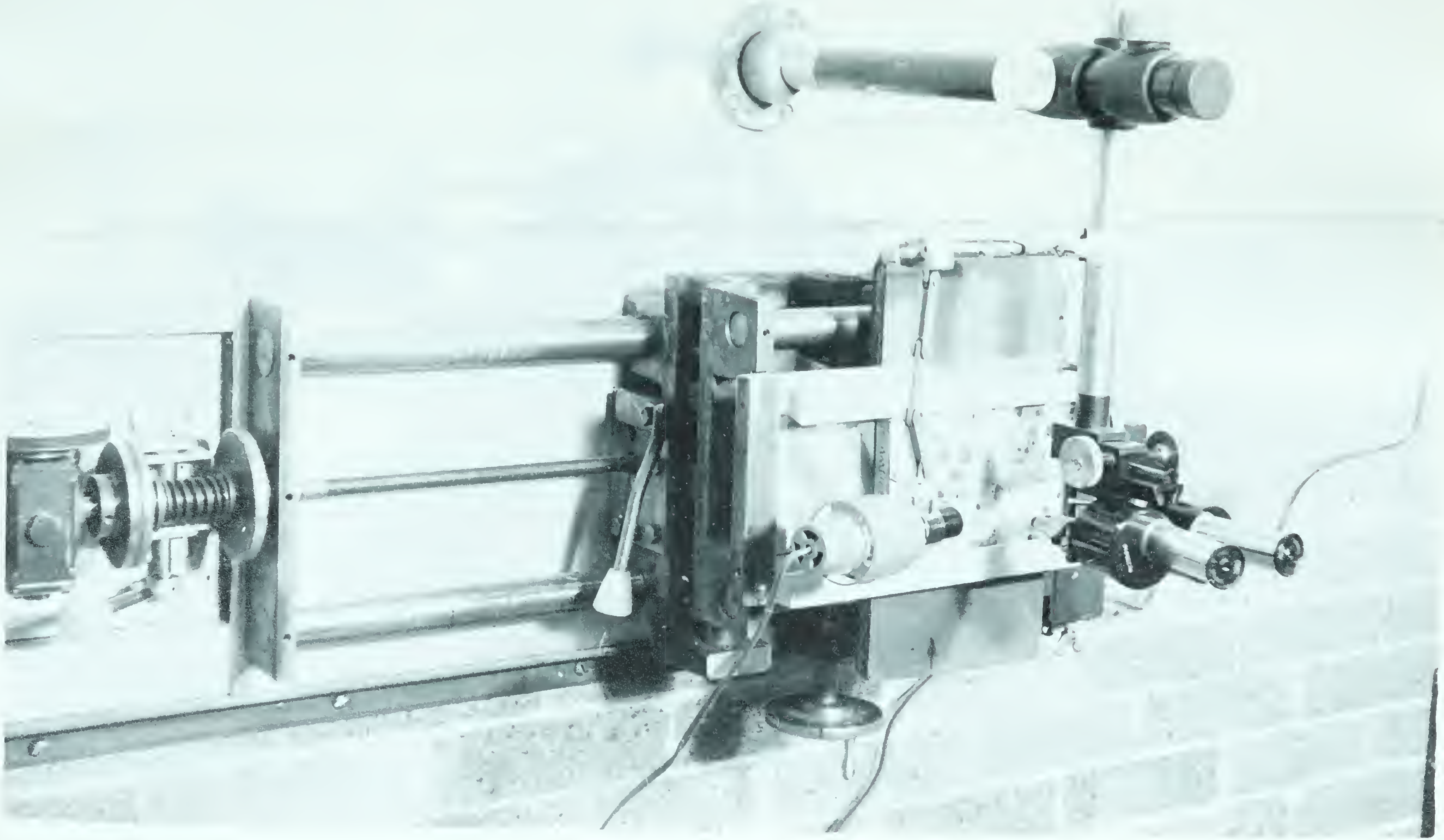


PLATE 4 TRAVERSING TABLE AND STEREOSCOPIC MICROSCOPE

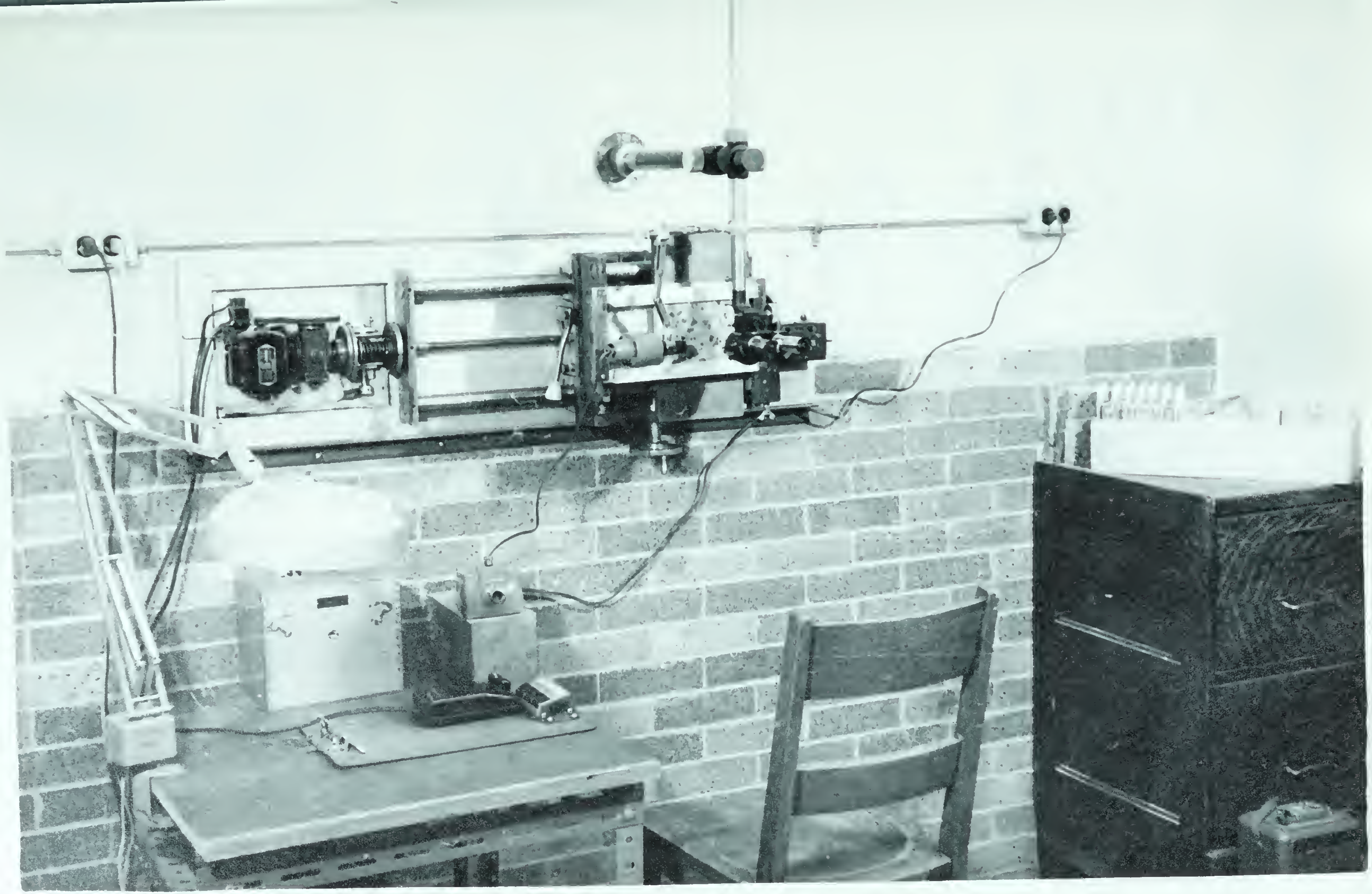


PLATE 5 OVERALL VIEW OF MICROSCOPIC ANALYSIS EQUIPMENT

3-5 MIXING AND FABRICATION OF SPECIMENS

The report of A.S.T.M. committee C-9 (1962) on concrete and concrete aggregate was followed for preparation of material and fabrication of laboratory specimens. Special reference was made to A.S.T.M. designation C192- of this report.

3-5-1 Preparation of Material

(a) The materials were brought to room temperature, (68° - 80° F.) before beginning the test.

(b) The cement was stored in dry moistureproof containers made of metal. It was thoroughly mixed in order that the sample would be uniform throughout the test.

(c) The two classes of aggregate were stored in separate bins. Prior to weighing, the amount of surface moisture on the coarse and fine aggregate was determined and appropriate allowance made in the batching of the materials.

2-5-2 Mixing Concrete

(a) General

The concrete was mixed in a rotating drum mixer in batches of such size as to leave about 10 per cent excess after molding test specimens. When calcium chloride was used, it was dissolved in water and added to the concrete as a portion of the mixing water.

(b) Buttering the Mixer

Prior to mixing the test batch, the mixer was "buttered" by mixing a batch proportioned to approximately the proportions of the test batch. The mortar adhering to the mixer after discharging was intended to compensate for loss of mortar from the test batch.

(c) Machine Mixing Procedure

(1) The total amount of coarse aggregate was added to the mixer.

(2) About 3/4 of the required mixing water was added and the mixer was turned on.

(3) The total measured quantity of cement was added and mixing was continued until the cement covered the coarse aggregate.

(4) The total measured amount of fine aggregate was added.

(5) Additional mix water was added to produce the required consistency as determined by the slump test.

(d) Time of Mixing, Slump and Air Content.

After all materials were in the mixer, a mixing period of 3 minutes, followed by 3 minutes rest, followed by 2 minutes final mixing was used. During the 3 minutes of rest the slump of the batch of concrete was measured and if required an adjustment in the amount of mixing water was made during the final 2 minutes of mixing. The slump test was made in accordance with A.S.T.M. designation C231. The concrete used for determination of air content was discarded. The apparent air content was maintained at $6.0 \pm 0.2\%$.

(e) Method of Consolidation

External vibration was used to consolidate the specimens. The molds were filled and vibrated in two approximately equal layers. Each layer was vibrated for approximately eight seconds. After the second layer was vibrated, enough concrete was added and worked into the underlying concrete with a trowel to overfill the mold by about 1/8 inch and then struck off.

3-6-3 Curing Specimens

Immediately after molding, the specimens were moved with a minimum of disturbance to a table in the concrete laboratory. They were covered with a layer of polyethylene to prevent moisture loss and were left for 24 hours. The molds were then stripped and the specimens were placed in the saturated lime solution for further curing. The specimens were kept in the curing tank until they were required for testing.

3-6 TESTING PROCEDURES

3-6-1 Strength Testing

The compressive strengths were determined by the use of the hydraulically operated Baldwin Testing machine using the procedure as outlined in A.S.T.M. designation C39-56T, "Compressive Strength of Molded Concrete Cylinders." This test method states that in hydraulically operated machines the load shall be applied at a constant rate within the range of 20 to 50 psi per second. The rate of loading was maintained at 35 psi per second by the use of a built-in pacer in the Baldwin machine.

The indicated strength of concrete made and cured under the same conditions varies with the size and shape of the specimen. The strength of a 3" by 6" cylinder is about 106% that of a 6" by 12" cylinder (W.H. Price 1949). The values reported herein are those obtained on 3" by 6" specimens.

An important factor in compressive strength testing is the end-condition affect. For this investigation a mixture of three parts of sulfur and one part of fire clay was used, which compares to the strengths

obtained on cylinders with the ends ground to within 0.002 inches of a plain surface. (W. H. Price 1949)

3-6-2 Evaluation of Durability after Freezing and Thawing

When concrete specimens are frozen and thawed in water, two distinct types of disintegration have been observed; (1) The specimens may show little change in weight and appearance but large losses in strength and resilience; or (2) they may show progressive loss by crumbling and spalling but relatively little loss in strength and resilience of the remaining material. These are extremes and in many cases the concrete specimens will show both crumbling and loss of strength and resilience of the remaining material. (T.C. Powers 1945)

The methods used to evaluate the loss in durability due to freezing and thawing are varied, but are usually based on the following either singly or in combination: loss in compressive strength, loss in weight, reduction in dynamic modulus of elasticity, expansion, and/or visual and microscopic examination. Reduction in compressive strength and modulus of dynamic elasticity are most commonly used, but neither method distinguishes between the two general types of destruction. Since the reduction in compressive strength method requires a considerable quantity of samples, the method of reduction in dynamic modulus of elasticity is perhaps the more convenient of the two. This method of test, called the Sonic Modulus method is intended primarily for detecting significant changes in the dynamic modulus of elasticity of laboratory or field test specimens that are undergoing exposure to weathering or other types of potentially deteriorating influences.

During the laboratory freezing and thawing test, the progressive deterioration is best shown by the term called relative dynamic modulus of elasticity and is calculated as follows:

$$P_c = \frac{n_1^2}{n^2} \times 100$$

P_c = relative dynamic modulus of elasticity, per cent after "c" cycles of freezing and thawing.

n = fundamental transverse frequency at 0 cycles of freezing and thawing.

n_1 = fundamental transverse frequency after "c" cycles of freezing and thawing

At the end of a greeze-thaw test the durability factor is calculated as follows:

$$DF = \frac{PN}{M}$$

WHERE DF = durability factor of the test specimen

P = relative dynamic modulus of elasticity at N cycles -%

N = number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated whichever is less, and

M = specified number of cycles at which the exposure is to be terminated.

For field concrete placed in the fall or early winter, the first winter is likely to be the most critical, other factors remaining constant,

as the strength of the concrete may be relatively low due to incomplete curing and also the degree of saturation of the concrete is likely to be high. As an approximation of these conditions in the laboratory, a test age of 14 days was selected for all mixes. This resulted in the concrete specimens being tested at various strengths for comparable cement contents due to the accelerating effect of calcium chloride and the more rapid strength development of high early strength cement. This results in variation in durability due to strength variation as well as effects of calcium chloride. As an initial program this procedure was felt justified in limiting the experimental work involved. Since the air void parameters were to be determined by microscopic analysis it was felt that this would provide data upon which to predict the effect on durability at later ages since the strength differences would be slight.

3-6-3 Microscopic Analysis

For this investigation the procedure was based on A.S.T.M. designation C457-60T, "Microscopic Determination of Air Void Content, Specific Surface, and Spacing Factor of the Air-Void System in Hardened Concrete."

A detailed procedure of slab preparation is presented in the appendix of this report and will not be dealt with here. However the prime factors controlling the validity of the results are the quality of the finished surface of the concrete specimen and the area of the concrete over which the traverse is made. Care must be exercised in preparing the surface as shelling out of fine aggregate particles and rounding of edges of voids during preparation of the plane test surface increases the number and size of observed voids. Very little difficulty was generally encountered in

preparing surfaces of ordinary concrete that had been cured adequately. However, high air content, high water-cement ratio, lean concrete and deteriorated concrete presents problems in surface preparation. For example, at very high air contents the bubbles tend to coalesce and the thin septa and ridges between the voids are easily lost during grinding. Void parameters determined on such a surface usually are only approximations because numerous chord interceptions must be estimated. To minimize the difficulties of surface preparation, impregnation of the specimen with carnauba wax to strengthen and support the near surface concrete was extremely helpful. This method of impregnating is described quite fully in the appendix of this report and will not be dealt with here.

For this investigation the stereoscopic microscope was used at a magnification factor of 90X. Some investigators feel that scanning of the surfaces at this magnification is intolerably slow and tedious (L.S. Brown and C.U. Pierson 1951). They maintain that magnifications of 30X to 40X are adequate. However it is the author's opinion that higher magnifications are desirable in order to make more positive identification of the smaller voids. Also some investigators reported that the specific surface is increased and that the spacing factor is decreased as the magnification is increased.

Perhaps the only apparent disadvantage the use of high order magnification presented was that the prepared surface should be of a superior ground finish. Suitable surfaces were obtained easily and quickly by the use of the procedure outlined in the appendix of this report. A carefully

polished surface not only increased the accuracy of the work but also speeded up the actual scanning and observation with the microscope. The author found that this aspect of the investigation was slow and tedious so that any extra efforts taken to reduce the actual observation time were well warranted.

One of the commonly raised questions is whether or not entrained air is distinguishable from entrapped air. No attempt was made to distinguish these as the survey represents a summation of all void spaces observed. For one thing there was no secure way to establish a size range distinction between the one and the other. Even if a critical size were established, the true diameter of a void was not always perceivable on a random section. For another thing measurement of air in hardened concrete in practice is commonly made as a check against air as determined by pressure meter in the fresh concrete. Air indicated by the pressure meter is a summation of all void space, as the pressure meter does not distinguish between entrained and entrapped air.

Another problem in microscopic work is to distinguish water voids from air voids. L.S. Brown (1959) states that water voids are readily recognizable as such and when they appear they practically always are in the form of thin shell-like openings resulting from sub-aggregate bleeding. Furthermore he maintains that they are rarely encountered in good concrete, and that in the traverse should be ignored. R.C. Mielenz et al (1957) maintains that the traverse should include all air voids observed in the surfaces, including the occasional openings apparently resulting from bleeding and settlement of fresh concrete. According to Mielenz, these

should be included in the analysis for two reasons: (1) to attempt to eliminate them introduces a subjective factor in the measurements and (2) such voids, once emptied of water by drying of the concrete or as a result of the curing and hydration process, act as air voids just as do "entrapped" air of equal surface area, even though both are relatively insignificant in their affect on frost or scaling resistance.

In this investigation water voids (water cavities) were ignored. The author felt that they could readily be recognized as water voids due to their irregular boundaries, larger size and positioning which in the majority of cases occurred below larger sized aggregate particles. Also in this investigation an attempt was made to correlate freeze-thaw durability and the air void parameters of the concrete. Prior to freeze-thaw testing the curing process of the specimens was such as to maintain a high level of saturation. Since the freeze-thaw testing procedure used was rapid freezing and thawing in water, drying of the water cavities was not likely. Consequently the water voids were assumed to have been kept saturated and it was assumed that they did not provide any beneficial effect on the concrete.

The shelling out of fine aggregate during the polishing process presents another problem in the microscopic analysis. These small pits remaining after polishing are difficult to differentiate from the air voids and may be included in the air-void traverse. However careful polishing, it was felt, minimized shelling out of fine aggregate and thus made this problem of negligible importance.

In certain cases a small quartz aggregate will be crystal clear

and present some difficulty in distinguishing it as an aggregate, especially in a monocular view directed normal to the surface. Such uncertainty is reduced substantially to zero in surface scanning by a stereoscopic microscope with illumination from one direction and incident at a low angle, around 15 to 30 degrees from the horizontal. With this arrangement, and a suitably prepared surface, recognition of air voids was relatively easy.

CHAPTER IV

TEST RESULTS

4-1 GENERAL

The results of this investigation have been summarized and are presented in tabular and graphical form. Three main types of testing have been done, namely; compressive strength, freeze-thaw durability and microscopic analysis of polished concrete sections. Each phase of testing is discussed independently and then an attempt is made to correlate these results for the final conclusions.

4-2 COMPRESSIVE STRENGTH

TABLE IX presents a summary of the compressive strength results for the 18 mixes tested. These values are plotted in FIGURES 6, 7, and 8 as compressive strength versus age in days.

It should be emphasized that the compressive strength testing was done primarily as a control measure in this investigation. Consequently the relationship between the strength developed upon the additions of varying percentages of calcium chloride as an admixture was not a major consideration, so that the data presented is not sufficient to make conclusive statements, although apparent trends can be discussed.

FIGURES 6, 7 and 8 show the typical strength development of concrete made and cured under similar conditions with varying percentages of added calcium chloride. It can be concluded from these results that at casting and curing temperatures around 70° F. the strength of the concrete at all ages up to 28 days was improved by the addition of calcium chloride. The

very early (up to 7 days) strength development of the concrete increased as the percentage of calcium chloride was increased up to 3 per cent.

For the lean concrete (400 lbs./cu.yd.) the maximum 28-day strength gain due to the addition of 1% calcium chloride was 38% . For the intermediate concrete (550 lbs./cu.yd.) this gain in 28-day compressive strength dropped to 13% for an addition of 2% calcium chloride, whereas for the rich concrete (700 lbs./cu.yd.) the maximum gain in 28-day compressive strength was 17% for an addition of 2% calcium chloride.

From the above statement and with reference to FIGURE 9, the relationship between 28-day compressive strength and water cement ratio, it is seen that the percentage gain in 28-day compressive strength is greater at high water cement ratios than at low water cement ratios.

In comparing the air-entrained, and non-air-entrained mixes, with no calcium chloride admixture, FIGURE 9 shows that the air-entrained mixes have a reduction in 28-day compressive strength of about 30%. This is in agreement with W. H. Price's (1949) general statement that the strength of concrete is reduced about 5% for each percentage of air-entrainment when the water cement ratio is held constant.

FIGURE 9 shows that for air-entrained concretes, the 28-day compressive strength using high early strength cement is substantially higher than for normal cement at the same water cement ratio.

TABLE IX

SUMMARY OF COMPRESSIVE STRENGTH TESTING P.S.I.

DESCRIPTION OF SAMPLE	7 DAY STRENGTH	14 DAY STRENGTH	28 DAY STRENGTH
N-400-0	1430	2075	2470
6N-400-0	1330	1750	2110
6N-400-1	1920	2510	2920
6N-400-2	2040	2230	2790
6N-400-3	2210	2580	2910
6HE-400-0	2490	2930	3170
N-550-0	2830	3880	4330
6N-550-0	2760	3260	3860
6N-550-1	2940	3380	4300
6N-550-2	3160	3610	4360
6N-550-3	3130	3770	4080
6HE-550-0	3560	4180	4470
N-700-0	4350	5060	6140
6N-700-0	4060	4440	5010
6N-700-1	4140	4780	5550
6N-700-2	4630	5040	5870
6N-700-3	4480	5250	5330
6HE-700-0	4060	4760	5280

* - EACH VALUE IS AN AVERAGE OF 4 - 3INCH BY 6 INCH CYLINDERS

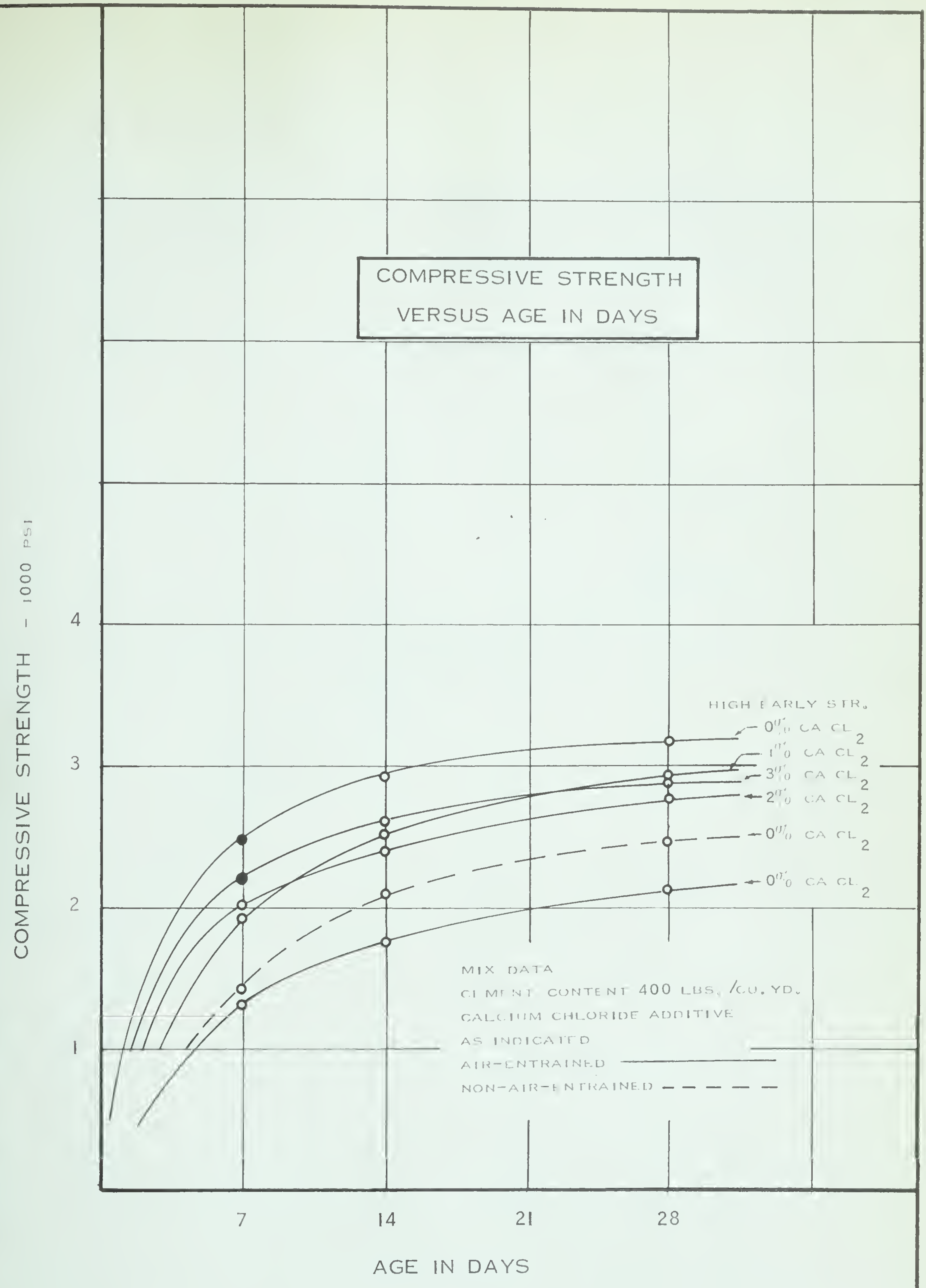

COMPRESSIVE STRENGTH
VERSUS AGE IN DAYS
COMPRESSIVE STRENGTH - 1000 PSI
1
2
3
4
7
14
21
28
AGE IN DAYS
HIGH EARLY STR.
0% CA CL 2
1% CA CL 2
3% CA CL 2
2% CA CL 2
0% CA CL 2
0% CA CL 2
MIX DATA
CEMENT CONTENT 400 LBS. /CU. YD.
CALCIUM CHLORIDE ADDITIVE
AS INDICATED
AIR-ENTRAINED
NON-AIR-ENTRAINED

FIGURE 6

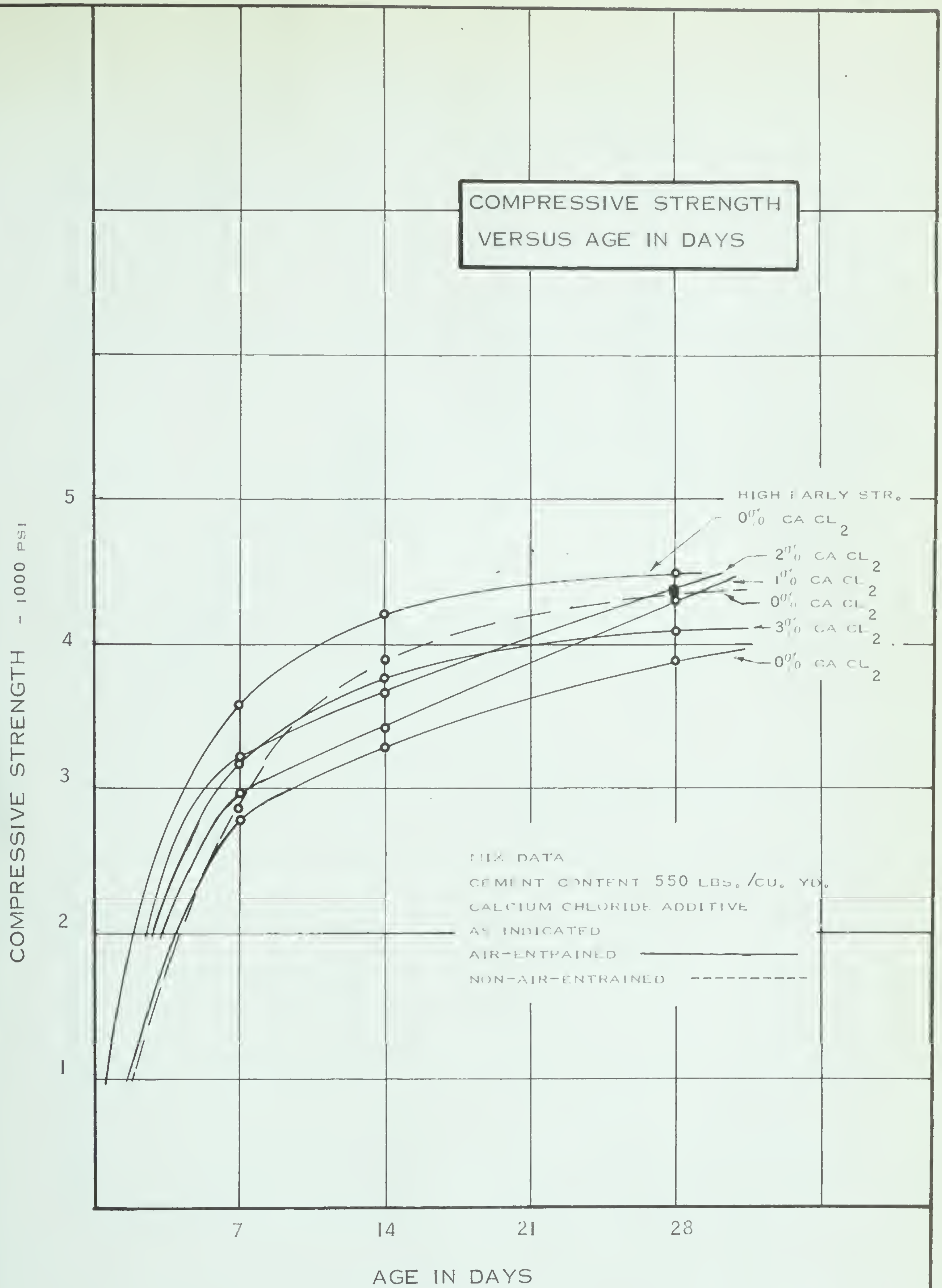

COMPRESSIVE STRENGTH
VERSUS AGE IN DAYS
COMPRESSIVE STRENGTH - 1000 PSI
1
2
3
4
5
7
14
21
28
AGE IN DAYS
HIGH EARLY STR.
0% CA CL2
2% CA CL2
1% CA CL2
0% CA CL2
3% CA CL2
0% CA CL2
MIX DATA
CEMENT CONTENT 550 LBS./CU. YD.
CALCIUM CHLORIDE ADDITIVE
AS INDICATED
AIR-ENTRAINED
NON-AIR-ENTRAINED

FIGURE 7

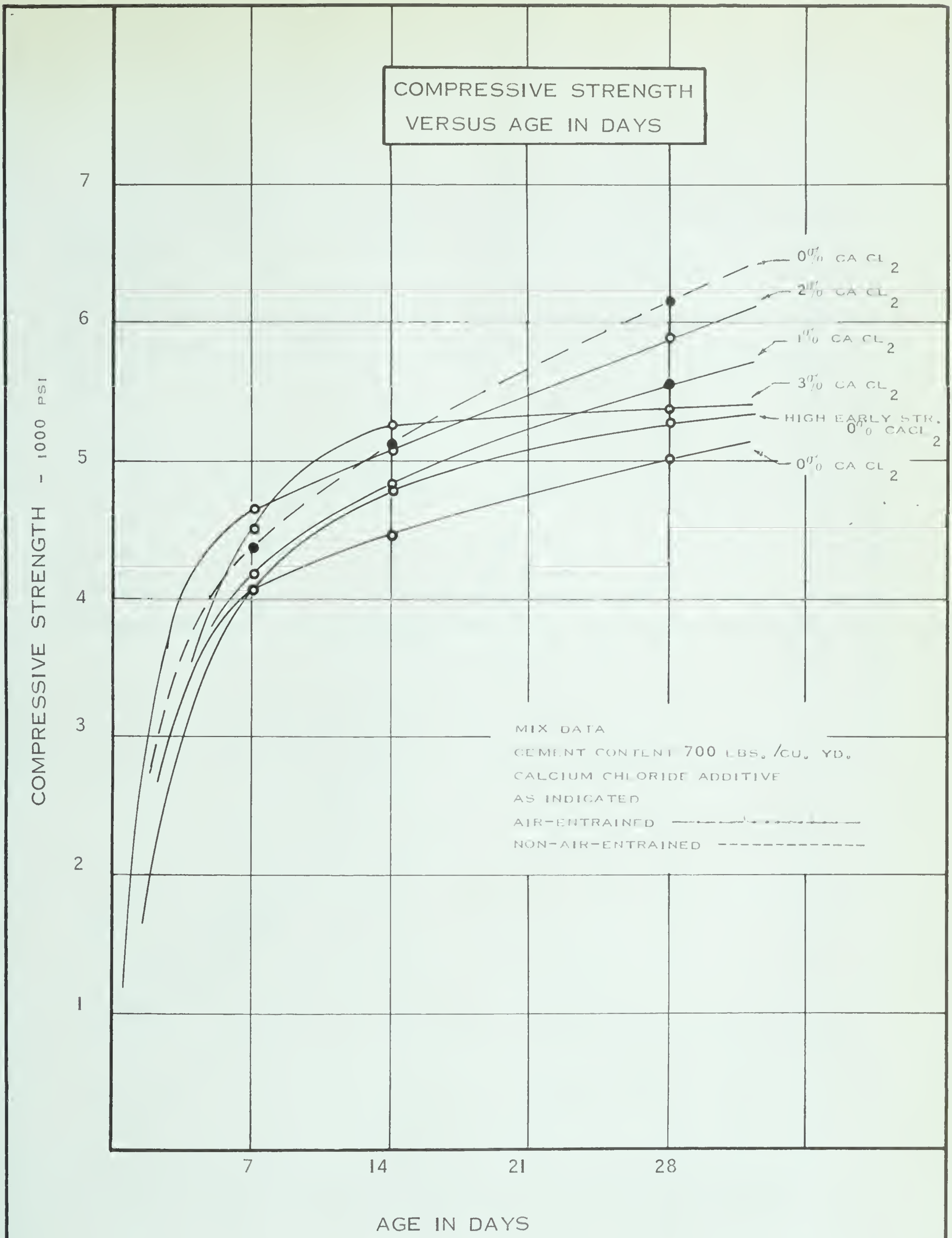

COMPRESSIVE STRENGTH
VERSUS AGE IN DAYS
COMPRESSIVE STRENGTH - 1000 PSI
1
2
3
4
5
6
7
7
14
21
28
AGE IN DAYS
0% CA CL 2
2% CA CL 2
1% CA CL 2
3% CA CL 2
HIGH EARLY STR. 0% CACL 2
0% CA CL 2
MIX DATA
CEMENT CONTENT 700 LBS. /CU. YD.
CALCIUM CHLORIDE ADDITIVE
AS INDICATED
AIR-ENTRAINED
NON-AIR-ENTRAINED

FIGURE 8

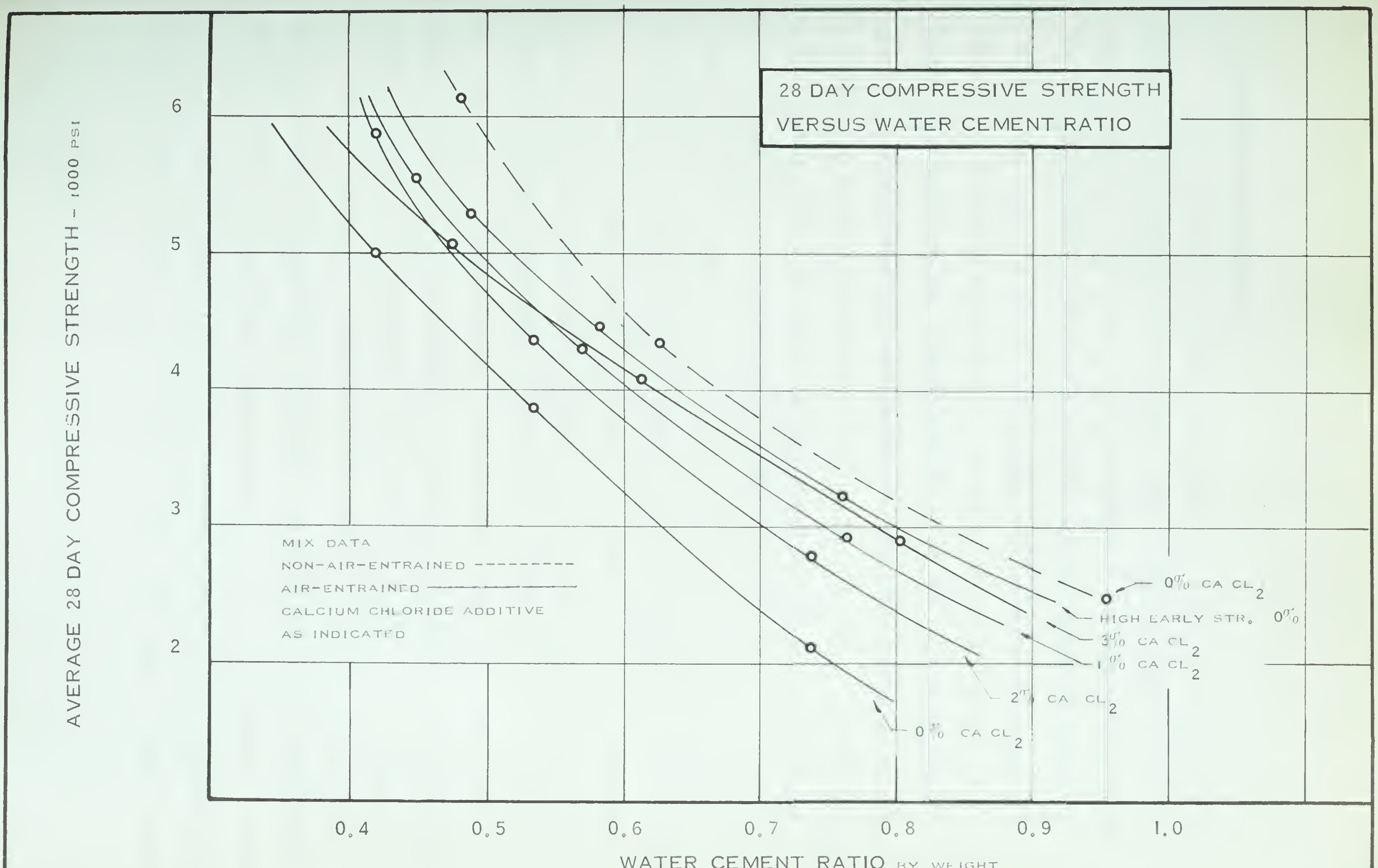

28 DAY COMPRESSIVE STRENGTH
VERSUS WATER CEMENT RATIO
AVERAGE 28 DAY COMPRESSIVE STRENGTH - 1000 PSI
6
5
4
3
2
MIX DATA
NON-AIR-ENTRAINED ---------
AIR-ENTRAINED
CALCIUM CHLORIDE ADDITIVE
AS INDICATED
0% CA CL2
HIGH EARLY STR. 0%
3% CA CL2
1% CA CL2
2% CA CL2
0% CA CL2
0.4
0.5
0.6
0.7
0.8
0.9
1.0
WATER CEMENT RATIO BY WEIGHT

FIGURE 9

4-3 FREEZE-THAW DURABILITY

The results of the freeze-thaw durability tests are shown on data sheets in the appendix of this report. The results of these tests are summarized in FIGURES 10, 11, and 12, which show the relationship between the relative dynamic modulus of elasticity and the number of cycles of freezing and thawing exposure. The very great difference in durability between air-entrained and non-air-entrained concretes is evident at a glance from these graphs. The deterioration of the non-air-entrained concrete was very rapid and testing was discontinued on them after only 44 cycles of freezing and thawing as the durability factor dropped to about 1% for the beams with a cement content of 400 lbs./cu.yd. and to 13.8% for the beams with a cement content of 700 lbs./cu.yd. All of the air-entrained concrete beams withstood the full 300 cycles of freezing and thawing; at the end of which the durability factor ranged from 63% to 84%.

The difference between the durability factor for the air-entrained concrete beams fabricated using normal portland cement and the air-entrained concrete beams using the high early strength portland cement was very slight. With reference to the graphs at the three different cement contents, it is shown that differences in durability are within 5%, which is within the experimental error possible in this test (Figures 10, 11, and 12). Therefore no significant difference in durability between these two types of cement was determined from the freeze-thaw investigation. Swenson (1955) stated, "Variations in durability due to difference in cements are not usually of major importance. Fineness appears to affect durability because of its influence on the water required. High early strength cements

with the greatest fineness show the least resistance to freezing and thawing."

The effect of the addition of varying percentages of calcium chloride to concrete appears to be dependent upon the cement content of the concrete. For the low cement content (400 lbs./cu-yd.), the addition of calcium chloride appears to be beneficial to the freeze-thaw durability. However, this increased resistance to freeze-thaw durability for the low cement content decreases until there is no appreciable difference at the medium cement content (550 lbs./cu.yd.) and finally at the high cement content (700 lbs./cu.yd.) it appears that calcium chloride is detrimental to the freeze-thaw durability.

The truth of the previous statement is further indicated in FIGURE 13 which shows the relation between durability factor and water cement ratio. This graph summarizes the results of the freeze-thaw investigation. It shows that for no added calcium chloride, the durability factor increases as the water cement ratio decreases. However upon adding increasing amounts of calcium chloride the relative increase in durability drops as the water cement ratio decreases.

At the high water cement ratios, it is difficult to draw any definite conclusions in regards to superior durability. However at the low water cement ratios it is evident that the superior durability was obtained with no calcium chloride admixture. As the amount of calcium chloride admixture was increased, the durability decreased. For example, at the water cement ratio of 0.4 the decrease in durability factor for 1% calcium chloride was 4.7%, for the 2% calcium chloride was 11.4% and for the 3% calcium chloride was 28.1%.

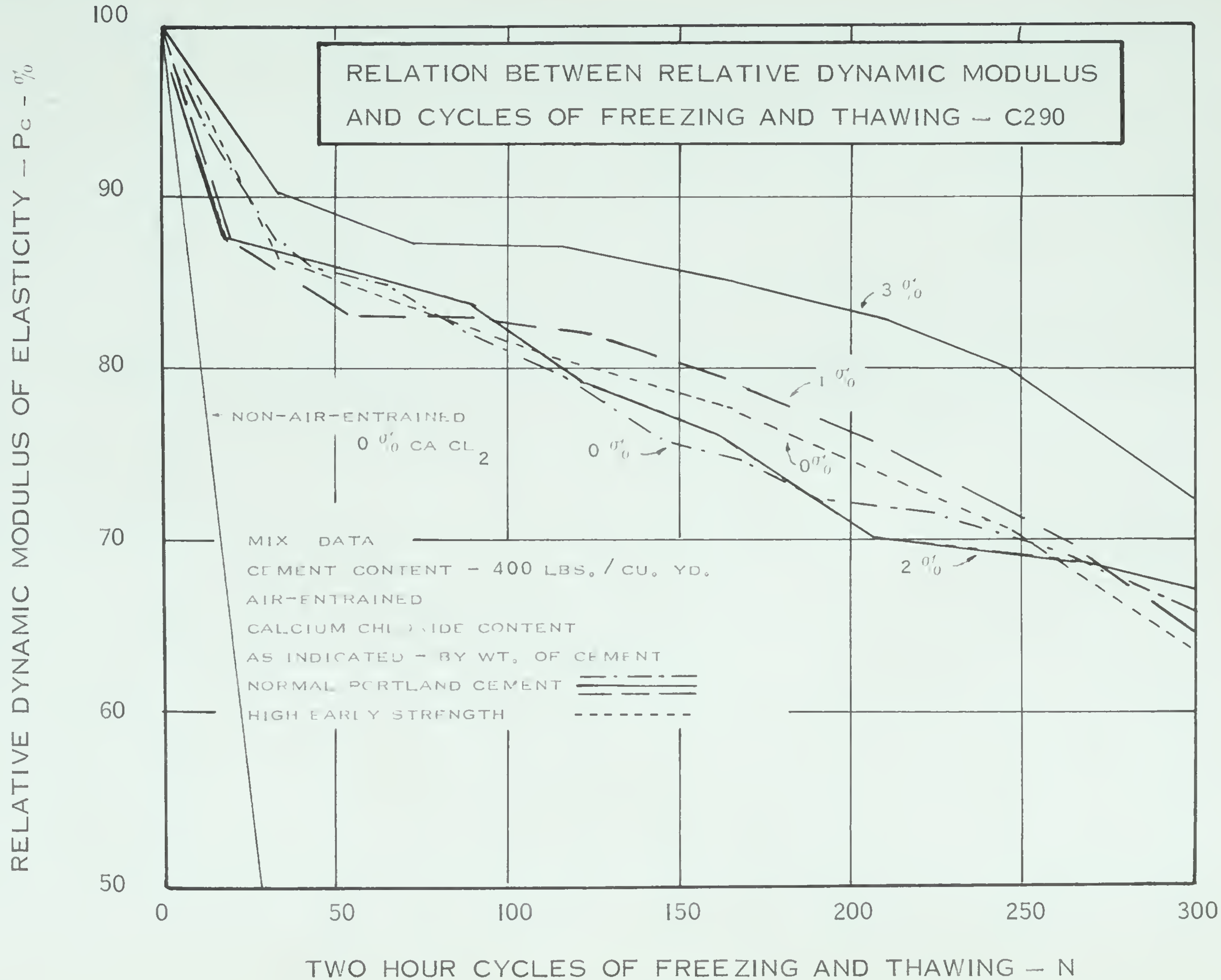

RELATION BETWEEN RELATIVE DYNAMIC MODULUS
AND CYCLES OF FREEZING AND THAWING — C290
RELATIVE DYNAMIC MODULUS OF ELASTICITY — Pc - %
100
90
80
70
60
50
0
50
100
150
200
250
300
TWO HOUR CYCLES OF FREEZING AND THAWING — N
3 %
1 %
0 %
0 %
2 %
NON-AIR-ENTRAINED
0 % CA CL 2
MIX DATA
CEMENT CONTENT - 400 LBS. / CU. YD.
AIR-ENTRAINED
CALCIUM CHL IDE CONTENT
AS INDICATED - BY WT. OF CEMENT
NORMAL PORTLAND CEMENT
HIGH EARLY STRENGTH

FIGURE 10

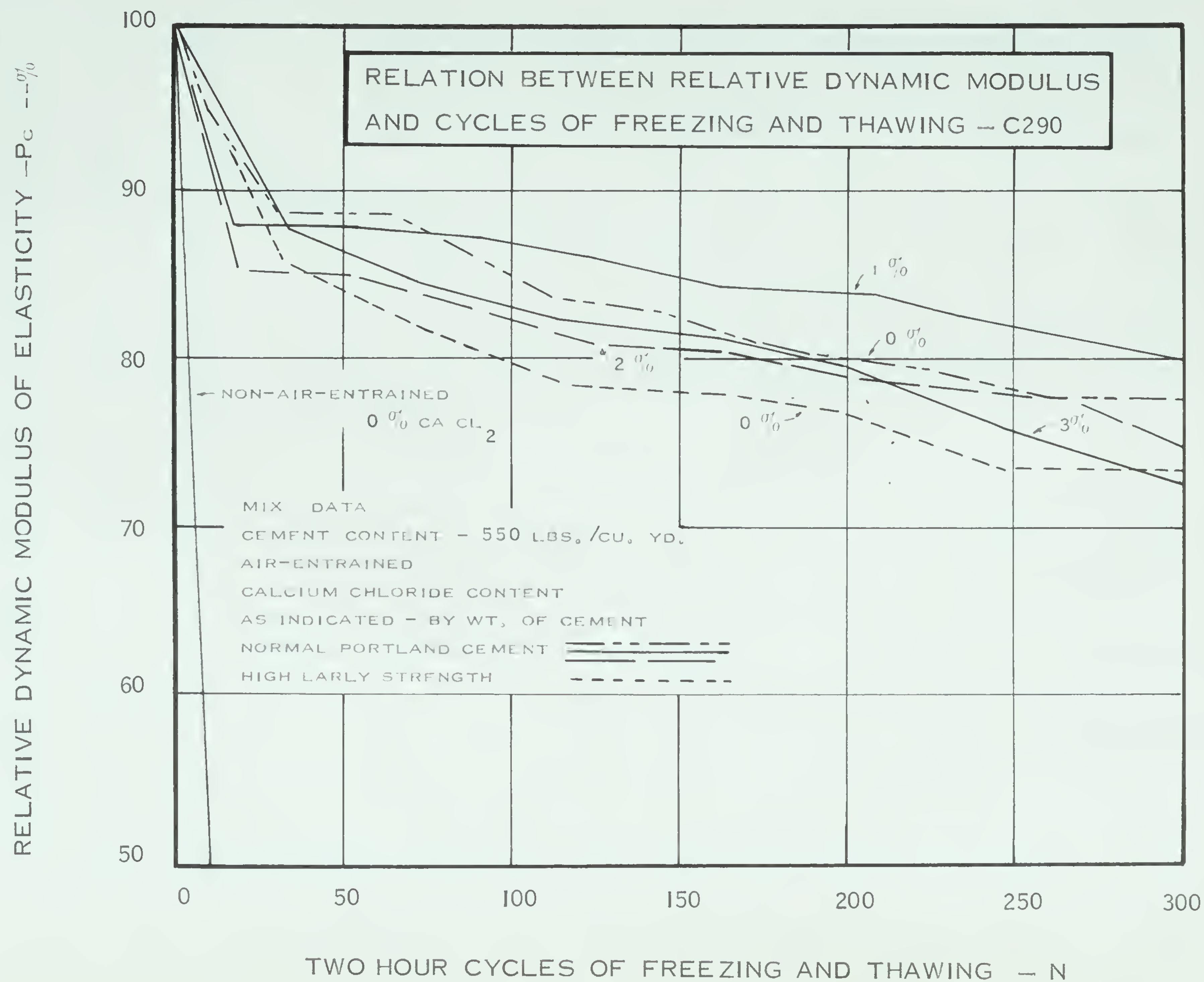
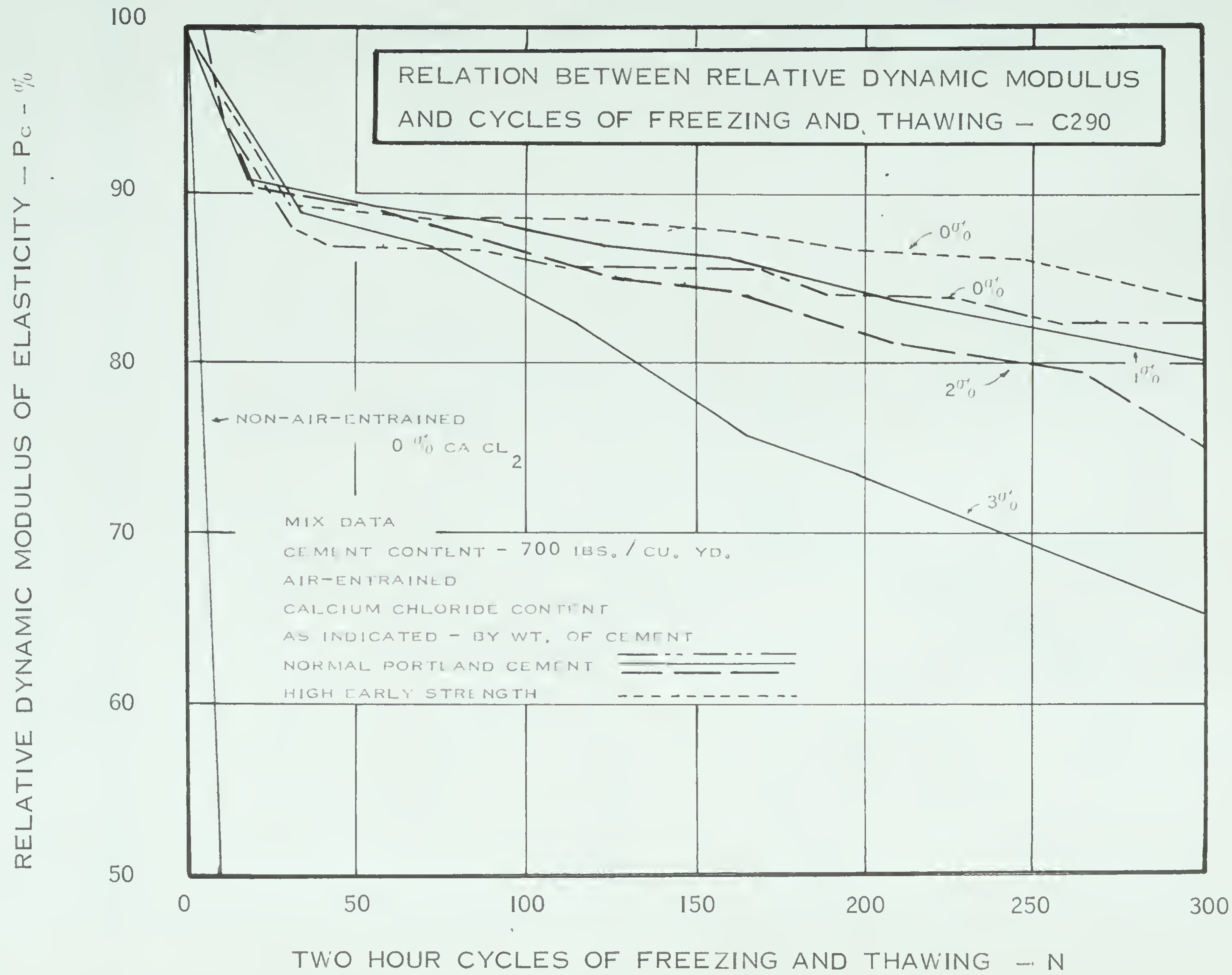


FIGURE 11

068



RELATION BETWEEN RELATIVE DYNAMIC MODULUS AND CYCLES OF FREEZING AND THAWING — C290
RELATIVE DYNAMIC MODULUS OF ELASTICITY — Pc - %
TWO HOUR CYCLES OF FREEZING AND THAWING — N
100
90
80
70
60
50
0
50
100
150
200
250
300
NON-AIR-ENTRAINED
0 % CA CL2
MIX DATA
CEMENT CONTENT - 700 lbs./CU. YD.
AIR-ENTRAINED
CALCIUM CHLORIDE CONTENT
AS INDICATED - BY WT. OF CEMENT
NORMAL PORTLAND CEMENT
HIGH EARLY STRENGTH
0%
0%
1%
2%
3%

FIGURE 12

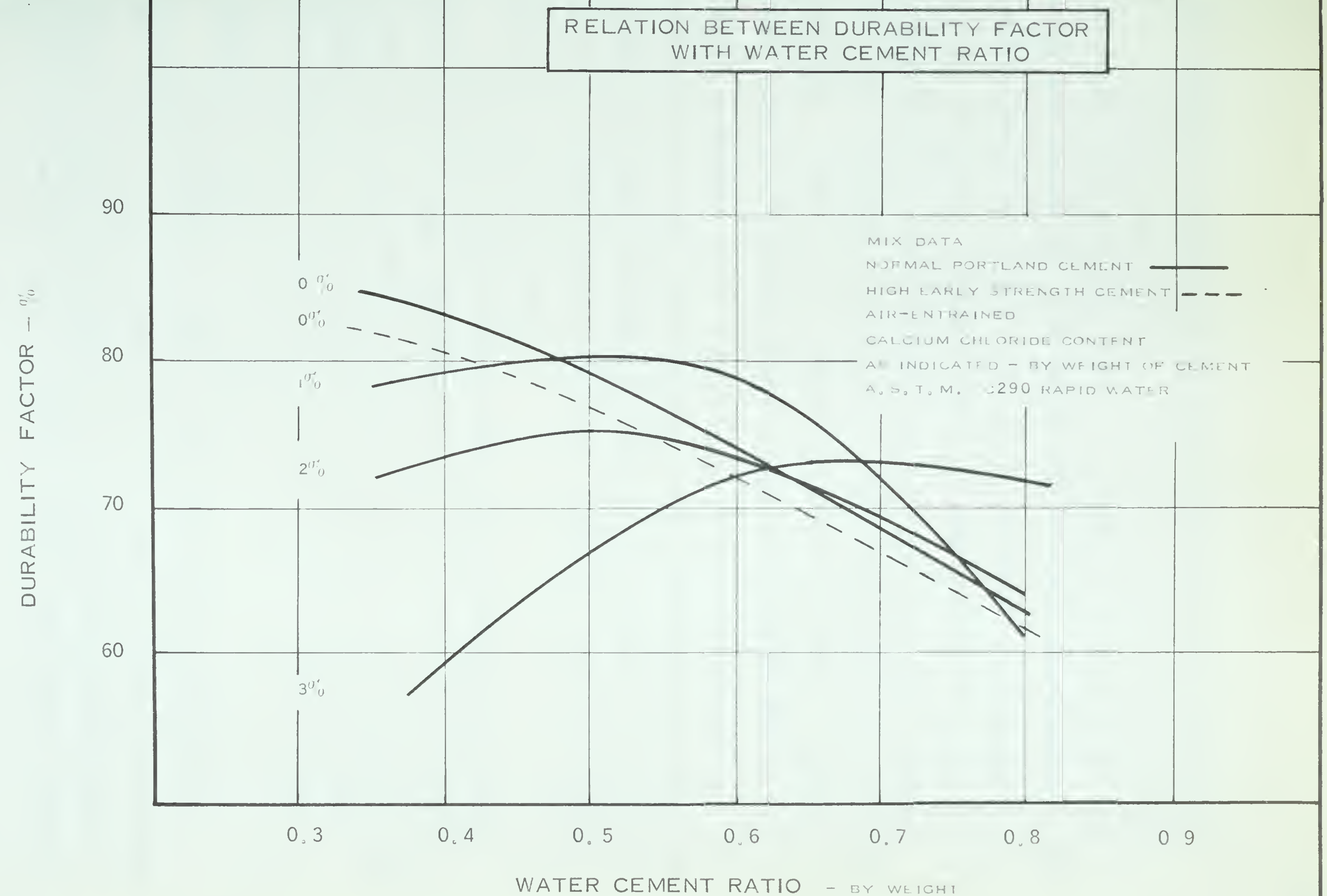

RELATION BETWEEN DURABILITY FACTOR
WITH WATER CEMENT RATIO
MIX DATA
NORMAL PORTLAND CEMENT
HIGH EARLY STRENGTH CEMENT
AIR-ENTRAINED
CALCIUM CHLORIDE CONTENT
AS INDICATED - BY WEIGHT OF CEMENT
A. S. T. M. C290 RAPID WATER
0 %
0%
1%
2%
3%
90
80
70
60
DURABILITY FACTOR - %
0.3
0.4
0.5
0.6
0.7
0.8
0.9
WATER CEMENT RATIO - BY WEIGHT

FIGURE 13

4-4 COMMENTS ON FREEZE-THAW DURABILITY BASED UPON VISUAL EXAMINATION

Surfaces finished with a steel trowel appeared to have superior resistance to scaling than surfaces cast against the steel molds lubricated with linseed oil. The initial sign of visual deterioration of the concrete beams was usually a deep pit in the concrete resulting from a pop out of aggregate or paste. This was attributed to the presence of a water cavity near the surface of the concrete which, upon freezing, the resulting dilation of the water in the cavity would force a piece of aggregate or paste from the side of the specimen leaving a large pit. These large pits were more numerous on the cast surfaces than on the trowelled surfaces. It is believed that in finishing a surface by trowelling, the large water cavities or air pockets immediately below the surface are worked out leaving the surface more resistant to pitting as the water cavities near the surface are eliminated, and those remaining are farther from the surface.

The first visible sign of surface scaling occurred after about 40 cycles of freezing and thawing for the lean concrete beams (400 lbs. cement/cu.yd.) and about 100 cycles for the rich concrete beams (700 lbs. cement/cu.yd.). For the latter, the surface scaling was very slight. The difference in scaling characteristics is quite evident from the photographs, PLATES 6, 7, 8 and 9.

With reference to PLATE 6, which shows the test specimens for 400 lbs./cu. yd. cement content after 300 cycles of freezing and thawing, it can be seen that the specimen with no added calcium chloride appeared to have the greatest amount of surface scaling. The remaining specimens

of 1%, 2%, and 3% added calcium chloride appeared to have about the same amount of surface scaling regardless of the percentage of calcium chloride. Similar results are evident in PLATES 7 and 8 for the intermediate and high cement content concrete specimens although perhaps not to as great an extent.

PLATE 9 compares all of the specimens investigated. The following will serve to identify the specimens.

A-	6N-700-1	K-	6HE-700-0
B-	6N-550-1	L-	6HE-550-0
C-	6N-400-1	M-	6HE-400-0
D-	6N-700-0	N-	6N-700-3
E-	6N-550-0	O-	6N-550-3
F-	6N-400-0	P-	6N-400-3
G-	N-700-0	Q-	6N-700-2
H-	N-550-0	R-	6N-550-2
J-	N-400-0	S-	6N-400-2

The above specimens were all exposed to 300 cycles of freezing and thawing except for the non-air-entrained specimens (G,H,J) which withstood 44 cycles.

Prior to freeze-thaw testing the initial weights of the concrete beams were determined. At the completion of the test the beams were reweighted. These results are shown in TABLE X.

The non-air-entrained concrete beams showed an increase in weight, except for the low cement content beams which lost weight as a result of

excessive deterioration. This increase in weight is attributed to the dilation of the non-air-entrained concrete beams upon freezing and then absorption of water during the thawing period. This has been observed and explained in some detail by previous investigators, (T.C. Powers and R.A. Helmuth 1953).

All the air-entrained concrete beams showed a weight loss at the end of 300 cycles of freezing and thawing. If this weight loss is related to surface scaling then it is evident that the results substantiate the visual observations made. The greatest weight loss occurred with the concrete beam with no calcium chloride admixture. The 1% and 2% added calcium chloride resulted in less weight loss. The 3% calcium chloride admixture was intermediate between the other two. This is shown graphically in FIGURE 14.

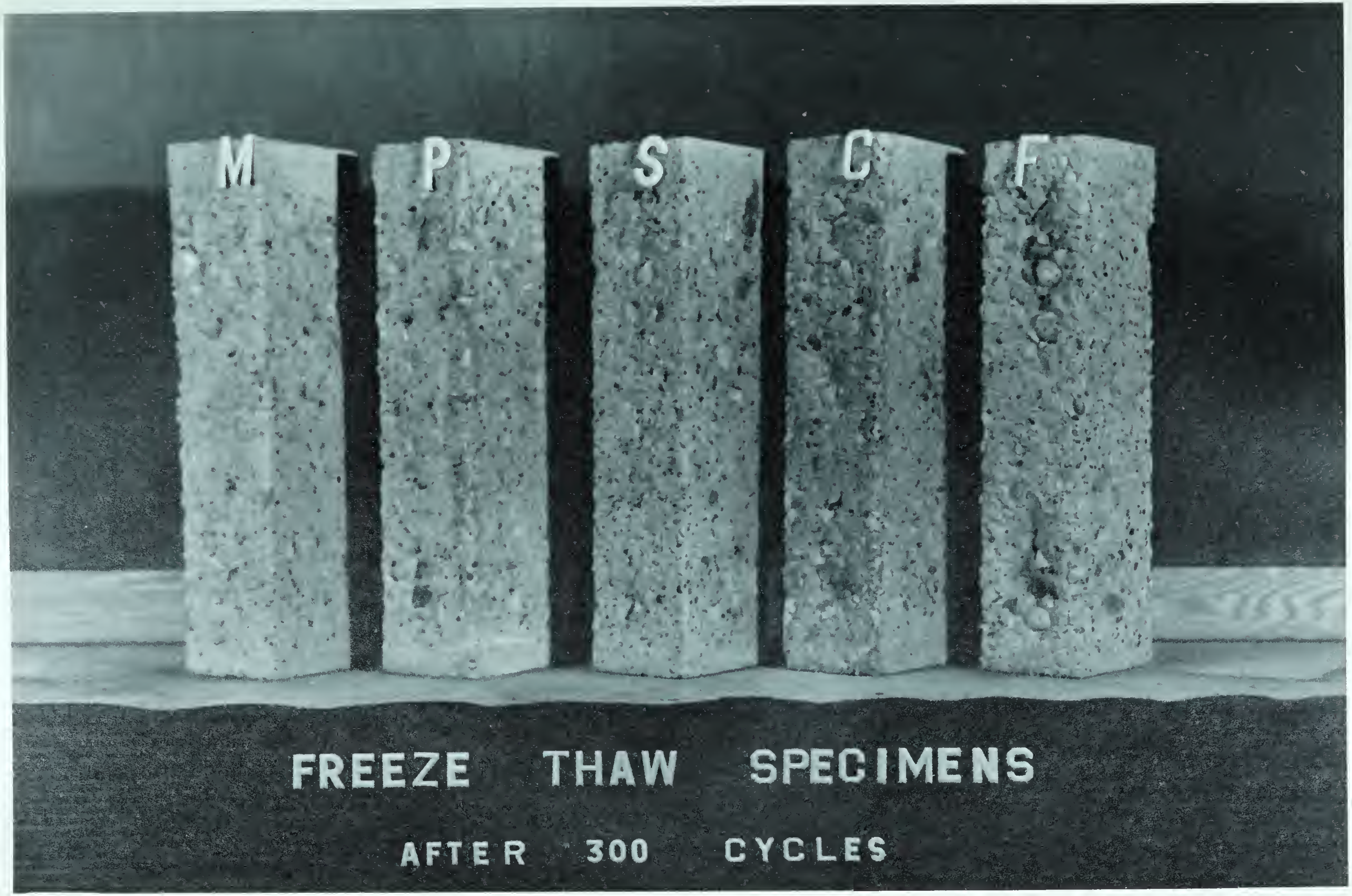


PLATE 6 FREEZE-THAW SPECIMENS M – 6HE-400-0,
P – 6N-400-3, S – 6N-400-2, C – 6N-400-1, F – 6N-400-0

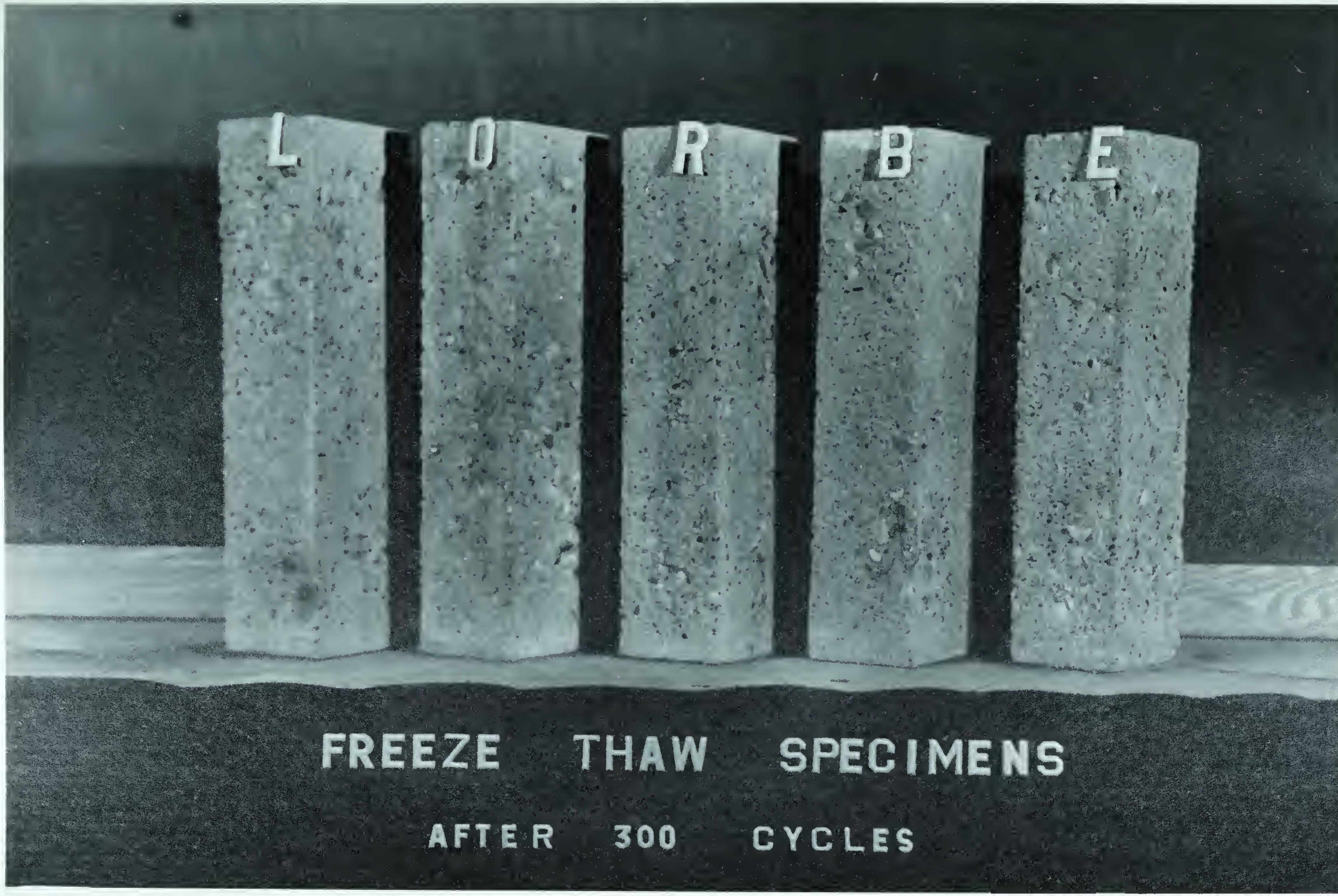


PLATE 7 FREEZE-THAW SPECIMENS L – 6HE-550-0,
O – 6N-550-3, R – 6N-550-2, B – 6N-550-1, E – 6N-550-0

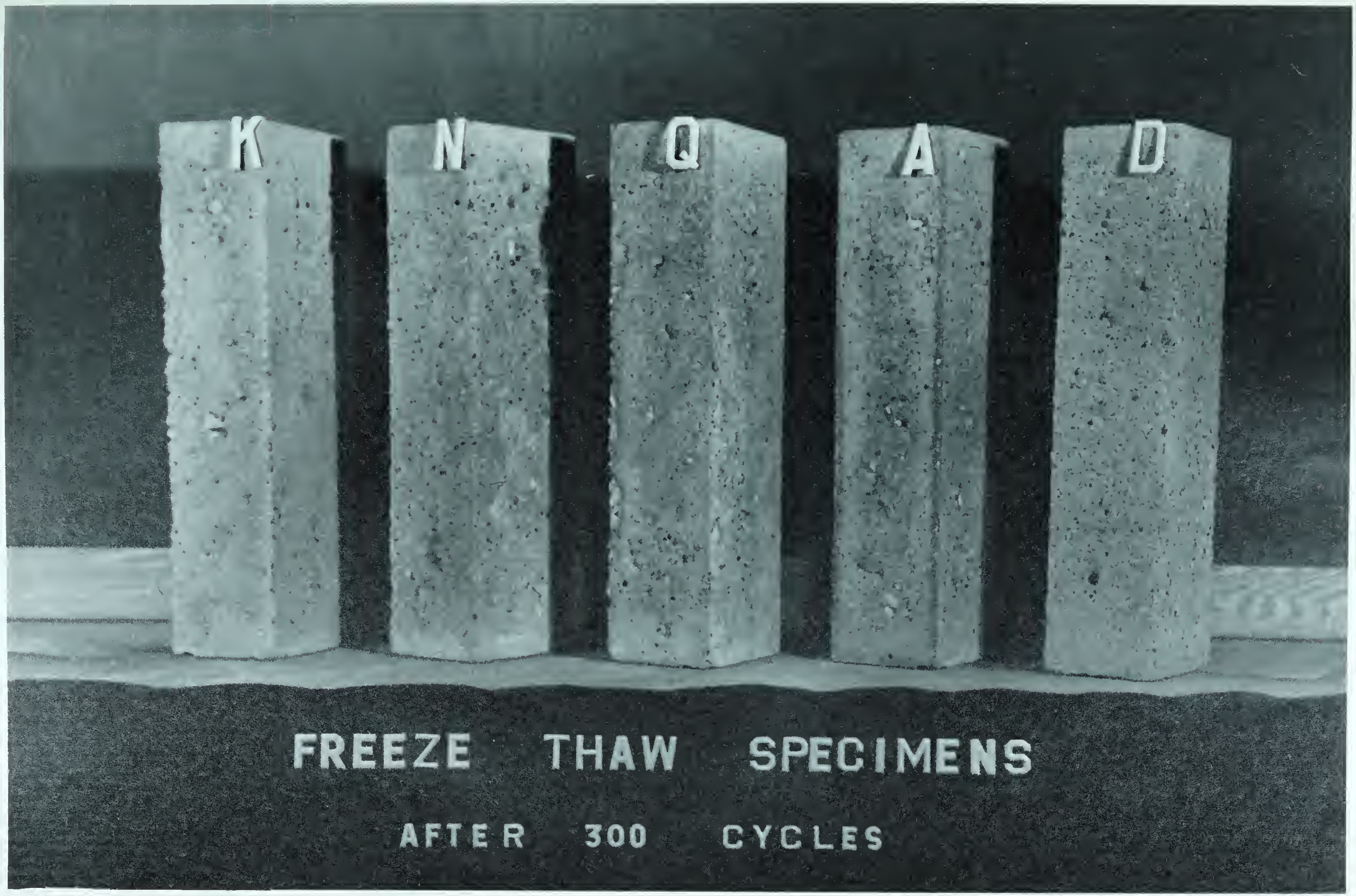


PLATE 8 FREEZE-THAW SPECIMENS K – 6HE-700-0,
N – 6N-700-3, Q – 6N-700-2, A – 6N-700-1, D – 6N-700-0

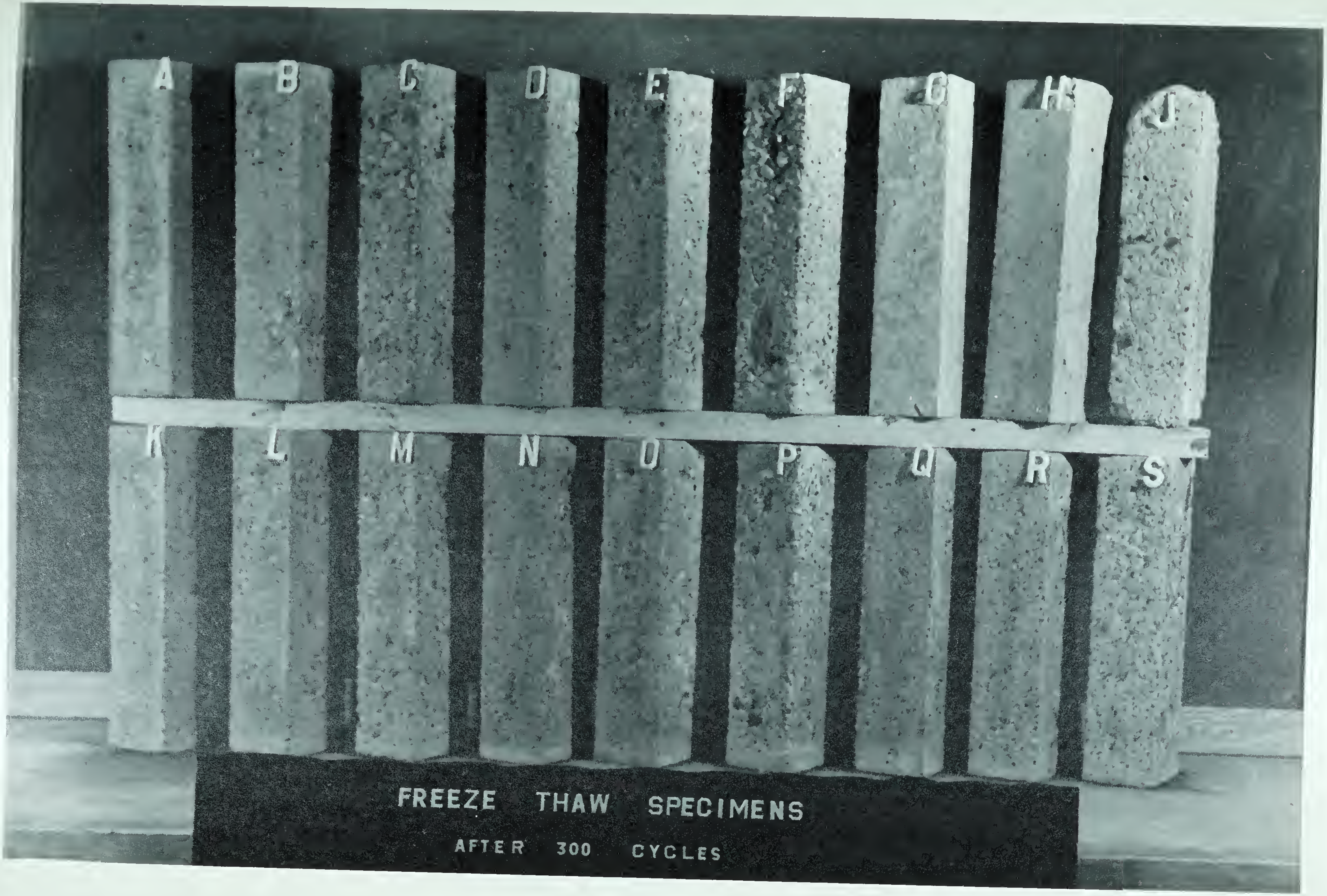


PLATE 9 OVERALL VIEW OF ALL FREEZE-THAW SPECIMENS

TABLE X

WEIGHT MEASUREMENTS ON FREEZE-THAW SPECIMENS

BEAM DESIGNATION		NO. OF CYCLES	INITIAL WT. GMS.	FINAL WT. GMS.	WT. LOSS OR GAIN GMS.
N-400-0	1	44	9637	9095	–522
	2	44	9663	9450	–213
N-550-0	1	65	9801	9855	54
	2	65	9766	9805	39
N-700-0	1	65	10135	10145	10
	2	65	10037	10062	25
6N-400-0	1	304	9410	8581	–829
	2	304	9286	8724	–562
6N-550-0	1	304	9568	9259	–309
	2	304	9518	9199	–319
6N-700-0	1	304	9690	9480	–210
	2	304	9640	9425	–215
6N-400-1	1	300	9597	9229	–368
	2	300	9638	9206	–432
6N-550-1	1	300	9537	9335	–202
	2	300	9556	9355	–201
6N-700-1	1	300	9570	9472	– 98
	2	300	9530	9430	–100
6N-400-2	1	300	9315	8912	–403
	2	300	9460	9062	–398
6N-550-2	1	300	9402	9155	–247
	2	300	9605	9380	–225
6N-700-2	1	300	9650	9561	– 89
	2	300	9560	9484	– 76
6N-400-3	1	300	9569	9162	–407
	2	300	9575	9165	–410
6N-550-3	1	300	9650	9347	–303
	2	300	9502	9197	–305
6N-700-3	1	300	9545	9361	–184
	2	300	9558	9388	–170
6HE-400-0	1	300	9492	9125	–367
	2	300	9573	9185	–388
6HE-550-0	1	300	9545	9352	–193
	2	300	9652	9226	–426
6HE-700-0	1	300	9415	9317	– 98
	2	300	9502	9400	–102

RELATIONSHIP BETWEEN LOSS IN WEIGHT AFTER 300 CYCLES OF FREEZING AND THAWING WITH CEMENT CONTENT

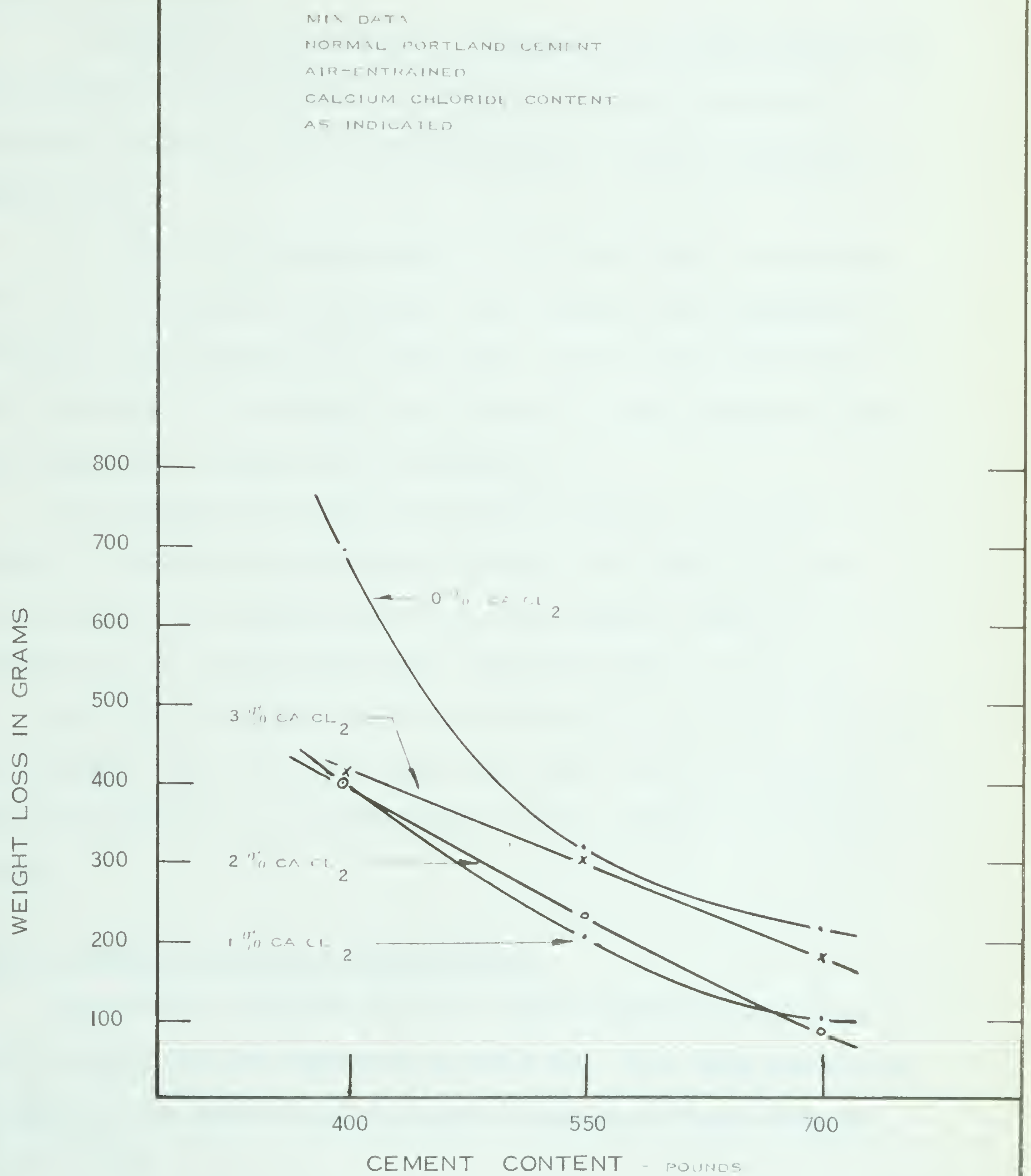


FIGURE 14

4-5 AIR VOID PARAMETERS

4.5-1 Air Content

A comparison of air content as measured on the fresh concrete by the pressure air meter and as measured on the hardened concrete by microscopic analysis showed a good correlation. TABLE XI summarizes these results.

The test for aggregate correction factor was made in accordance with A.S.T.M. designation C231-56T. This correction was determined directly on the aggregate as it was taken from the bin. This factor was determined to be 0.5% and it was assumed to remain constant for the given aggregate throughout the investigation.

As an additional check on the relative accuracy of the air content as determined by microscopic analysis, the results from this investigation were plotted directly with some results obtained by Bernard Erlin of the Portland Cement Association (1962), FIGURE 15. It is seen that the results from this investigation plot quite favorably on the graph. The bulk of the points plot above the line of equality, indicating that the air pressure meter gives the greater value for air content.

4-5-2 Specific Surface and Spacing Factor.

The air void characteristics and average durability factor for each laboratory mix are summarized in TABLE XII. This table constitutes a summary of the results which are shown in graphical form in FIGURES 16, 17, and 18.

According to T.C. Powers and colleagues (1949) air-entrainment in concrete increases durability by the dispersion throughout the cement paste of minute air bubbles which act as points of pressure relief from the hydraulic pressure generated by freezing of saturated concrete. If entrained air voids are present to the extent that no portion of paste is more than about 0.007 of an inch from an entrained air bubble, experience has shown that disruptive hydraulic pressures are unlikely to develop in the paste fraction of concrete under normal conditions.

It appears from TABLE XII that the addition of increasing amounts of calcium chloride tends to increase the average chord intercept (or the size of air bubble) and also decrease the number of air bubbles per inch. This results in a decrease in the specific surface and an increase in the spacing factor. The specific surface and the spacing factor are positively related to durability factor (F.K. Fears 1958) and as expected these changes in specific surface and spacing factor, as a result of the addition of calcium chloride, are detrimental to durability.

FIGURE 16 shows graphically the effects of added calcium chloride on specific surface, void spacing factor and the durability factor for various water cement ratios. It is interesting to note that the durability factor was slightly increased with an addition of 1% calcium chloride. This increase in durability factor may have been caused by the increase in specific surface of the air void system while the small increase in spacing factor was insufficient to cause any detrimental difference to the durability factor. Additions of 2% and 3% calcium chloride show a definite decrease in specific surface and an increase in spacing factor with a resultant decrease in durability factor.

The greatest loss in durability factor occurred at the lower water cement ratios. This trend was expected from the analysis of the air void parameters as the effect of added calcium chloride on the air void system was more marked at the lower water cement ratios. For an addition of 3% calcium chloride, at a water cement ratio of 0.8, the void spacing factor increased 12%. However for the same percentage of calcium chloride, at a water cement ratio of 0.4, the void spacing factor increased 32%. The effect of added calcium chloride on specific surface also varied extensively with the water cement ratio. At a water cement ratio of 0.8, the specific surface decreased 4% for an addition of 3% calcium chloride. The decrease in specific surface was 17% at a water cement ratio of 0.4 for the same addition of calcium chloride.

The relationship between durability factor with specific surface and with spacing factor is illustrated in FIGURE 17. The points plotted in this figure are values obtained for all the air-entrained mixes investigated. Although the points are scattered, a definite trend is indicated relating durability to specific surface and to spacing factor. Furthermore no differentiation can be made for the mixes with various percentages of added calcium chloride. This appears to indicate that the effect of calcium chloride on durability is basically due to the effect of calcium chloride on the air void parameters of hardened concrete. The durability factor of concrete appears to be more susceptible to the effects of calcium chloride on the air void parameters than to the effects of calcium chloride on the compressive strength. Since the addition of calcium chloride to concrete reduces the specific surface and increases the spacing factor, the durability is reduced even though the compressive strength of the

concrete is improved.

To obtain maximum durability of concrete exposed to cycles of freezing and thawing, a satisfactory air void system of the concrete is very important. Water contained within concrete when frozen can exert a hydraulic pressure of up to 29,000 psi which is far in excess of any paste strength possible. Therefore it is more important to relieve the hydraulic pressure with a satisfactory spacing factor than to design on the basis of strength alone.

FIGURE 19 shows the relationship between durability factor and average 14-day compressive strength. This figure illustrates the same relationship which was indicated when durability factor was plotted against water cement ratio. The 14-day compressive strength was chosen to represent the strength of the specimens at the start of the freeze-thaw testing.

FIGURE 20 was derived from FIGURE 19 and it shows the relationship between durability factor and percentage addition of calcium chloride for various 14-day compressive strengths. For no calcium chloride admixture, the durability factor is directly dependent on the compressive strength; the higher the compressive strength, the greater the durability factor. Upon additions of calcium chloride the durability factor drops quite rapidly for the high compressive strengths, and appears to increase slightly for the low compressive strengths. At 3% calcium chloride the durability factor appears to be similar for all the various compressive strengths.

This indicates that calcium chloride has a more pronounced effect

on durability (or air void parameters) at the high compressive strength than at lower compressive strengths. This trend substantiates the results obtained from FIGURE 13 where the conclusion was reached that the effect of added calcium chloride on the air void system is greater at low water cement ratios.

Another aspect of this investigation was to compare the durability characteristics of concretes made with normal portland cement to concretes made with high early strength cement. FIGURE 18 presents a graphical summation of the results obtained for different water cement ratios. Only three sections made from high early strength cement were analysed microscopically, and the variation in results made definite conclusions difficult to derive.

On the basis of the available test data, it appears that the durability of high early strength cement should be lower since the void spacing factor was greater. However, on the basis of constant water cement ratio, the difference in durability factor was quite small. This is perhaps attributed to the large differences of the compressive strengths of the specimens at the time of freeze-thaw testing. FIGURE 19, the relationship between durability factor and average 14-day compressive strength, shows that on the basis of constant 14-day compressive strength, high early strength cement has a lower durability factor.

Therefore when durability is compared on the basis of water cement ratio the high early strength gain of high early cement, appears to maintain the durability comparable to normal portland cement. When durability is

compared on the basis of comparable compressive strength, the use of high early strength cement appears to lower the durability factor about 15% at 2000 psi and 5% at 4500 psi (14-day compressive strength).

A previous statement implied that experience has shown that if the spacing factor is kept below 0.007 inches, no disruptive hydraulic pressures will develop. FIGURES 16 and 17 show that the spacing factors for the air-entrained mixeswere kept below this value. Since the air-entrained mixes withstood the full 300 cycles of a severe laboratory freezing and thawing test, this is evidence of a high degree of durability. This supports T.C. Powers (1955) calculations, that for average concrete able to withstand the freezing and thawing test, the spacing factor should be about 0.007 inch or less.

T.C. Powers (1955) states that the void spacing factor required to hold the rate of deterioration below a certain limit may vary from 0.005 inches to 0.01 inches for different laboratories depending upon the freezing rate used. No definite values are available for the freezing rates encountered in the field. Severe Canadian climatic conditions subjected to cold Arctic winds as well as warm Pacific chinook winds induce high freezing and thawing rates. Therefore durability is an extremely important factor in Canadian design and any adverse effects on durability should be considered.

4-6 SUMMARY OF TEST RESULTS

The results of the work completed in this investigation may be summarized as follows:

(1) At casting and curing temperatures around 70° F., the compressive strength of the concrete at all ages, up to 28 days was improved by the addition of calcium chloride (up to 3% by weight of cement).

(2) The rapid freezing and thawing in water laboratory test (ASTM C290-61T) for freeze-thaw durability distinguished quickly and decisively between the non-air-entrained concrete and the air-entrained concrete.

(3) For concretes with an adequate air void system, the durability factor depended upon the water cement ratio and also upon the percentage of added calcium chloride. Calcium chloride had a more marked effect at the lower water cement ratio where the durability factor decreased for increased percentages of calcium chloride added (up to 3% by weight of cement).

(4) During freeze-thaw testing, small additions of calcium chloride (1% and 2% by weight of cement) improved surface scaling resistance of the test specimens and decreased the weight loss of the test specimens.

(5) Comparison of air content as determined by the pressure meter in the fresh concrete with the air content as determined by microscopic analysis on the hardened concrete was satisfactory.

(6) At an early age (14 days curing), the durability factor of high early strength cement is similar to normal portland cement when compared on the basis of equal water cement ratios. However, when

compared on the basis of comparable compressive strength, the use of high early strength cement appeared to lower the durability.

(7) Additions of calcium chloride as an admixture to concrete showed a definite detrimental effect on the air void system of the concrete. This effect was greater at the lower water cement ratios which showed a large increase of 32% in spacing factor and a decrease of 17% in the specific surface for a water cement ratio of 0.4 by weight.

(8) The relationship between durability factor with specific surface and with spacing factor indicated a definite correlation between these air void parameters and durability.

TABLE XI

COMPARISON OF AIR CONTENT [% BY VOLUME] AS MEASURED ON FRESH CONCRETE AND AS MEASURED ON HARDENED CONCRETE

MIX DESIGNATION	AIR CONTENT OF FRESH CONCRETE A.S.T.M. C231 PERCENT BY VOLUME OF CONCRETE			AIR CONTENT ON HARDENED CONCRETE A.S.T.M. C457 PERCENT BY VOLUME
	APPARENT AIR CONTENT	AGGREGATE CORR. FACTOR	AIR CONTENT	
N-400-0	0.9	0.5	0.4	0.933
N-550-0	1.4	0.5	0.9	0.484
N-700-0	1.3	0.5	0.8	0.462
6N-400-0	6.0	0.5	5.5	4.84
6N-400-1	5.7	0.5	5.2	4.69
6N-400-2	5.9	0.5	5.4	5.12
6N-400-3	5.7	0.5	5.2	4.26
6HE-400-0	5.7	0.5	5.2	4.12
6N-550-0	5.7	0.5	5.2	4.96
6N-550-1	5.7	0.5	5.2	4.36
6N-550-2	6.0	0.5	5.5	5.19
6N-550-3	6.0	0.5	5.5	4.84
6HE-550-3	5.4	0.5	4.9	4.67
6N-700-0	6.0	0.5	5.5	4.84
6N-700-1	5.6	0.5	5.1	4.56
6N-700-2	5.5	0.5	5.0	4.50
6N-700-3	6.2	0.5	5.7	4.65
6HE-700-0	5.8	0.5	5.3	4.74

COMPARISON OF TEST RESULTS WITH PORTLAND CEMENT ASSOCIATION RESEARCH DEPARTMENT BULLETIN #149

[PAGE 26, TABLE 2 FOR 3 BY 6 INCH CYLINDERS]

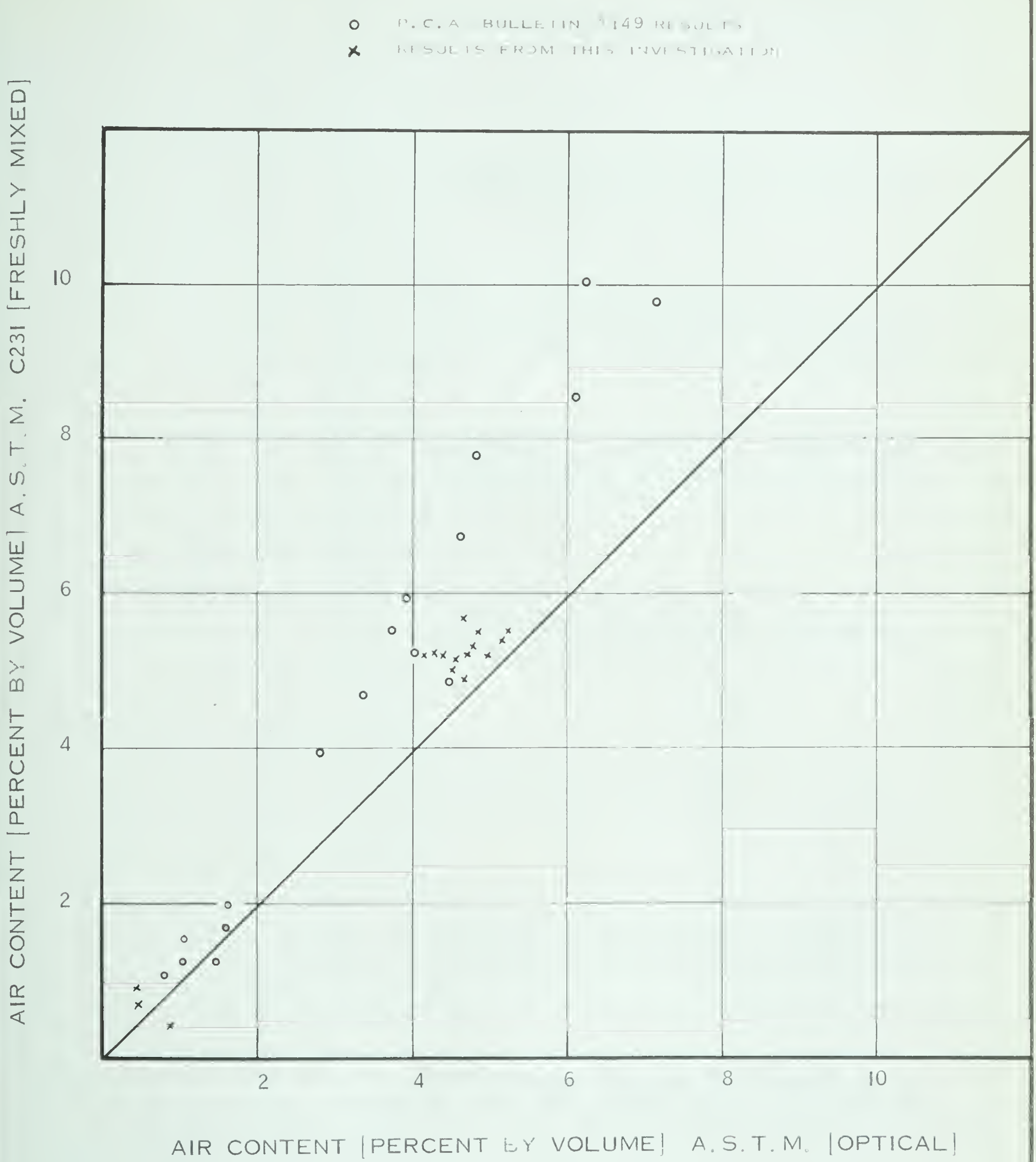


FIGURE 15

TABLE XII

AIR-VOID CHARACTERISTICS AND AVERAGE DURABILITY FACTOR FOR EACH LABORATORY MIX

MIX DESIGNATION	WATER CEMENT RATIO BY WEIGHT	DURABILITY FACTOR	CORRECTED AIR CONTENT [FRESH CONC.]	AIR VOID CHARACTERISTICS OF HARDENED CONCRETE				
				AIR CONTENT %	AVE. CHORD INTERCEPT IN.	VOIDS PER INCH	SPECIFIC SUR. SQ. IN/CU. IN.	SPACING FACTOR INCH.
N-400-0	.955	1.0	0.4	0.933	.0139	0.672	288	.0361
6N-400-0	.738	66.1	5.5	4.84	.00486	9.95	824	.00572
6N-400-1	.765	64.7	5.2	4.69	.00503	9.33	796	.00607
6N-400-2	.740	67.1	5.4	5.12	.00540	9.51	741	.00616
6N-400-3	.805	72.6	5.2	4.26	.00533	8.00	750	.00680
6HE-400-0	.772	63.1	5.2	4.12	.00483	8.53	828	.00616
N-550-0	.626	1.6	0.9	0.484	.0122	0.431	328	.0422
6N-550-0	.534	77.5	5.2	4.96	.00406	12.20	986	.00492
6N-550-1	.572	79.9	5.2	4.36	.00392	11.10	1020	.00515
6N-550-2	.534	75.1	5.5	5.19	.00437	11.89	915	.00521
6N-550-3	.613	72.7	5.5	4.84	.00490	9.88	817	.00617
6HE-550-0	.584	73.5	4.9	4.67	.00484	9.65	827	.00617
N-700-0	.482	13.8	0.8	0.462	.00806	0.573	496	.0294
6N-700-0	.418	82.5	5.5	4.84	.00370	13.10	1081	.00475
6N-700-1	.450	80.0	5.1	4.56	.00356	12.80	1123	.00477
6N-700-2	.418	74.0	5.0	4.50	.00372	12.10	1075	.00496
6N-700-3	.474	65.3	5.7	4.65	.00453	10.30	884	.00604
6HE-700-0	.489	83.5	5.3	4.74	.00348	13.60	1150	.00464

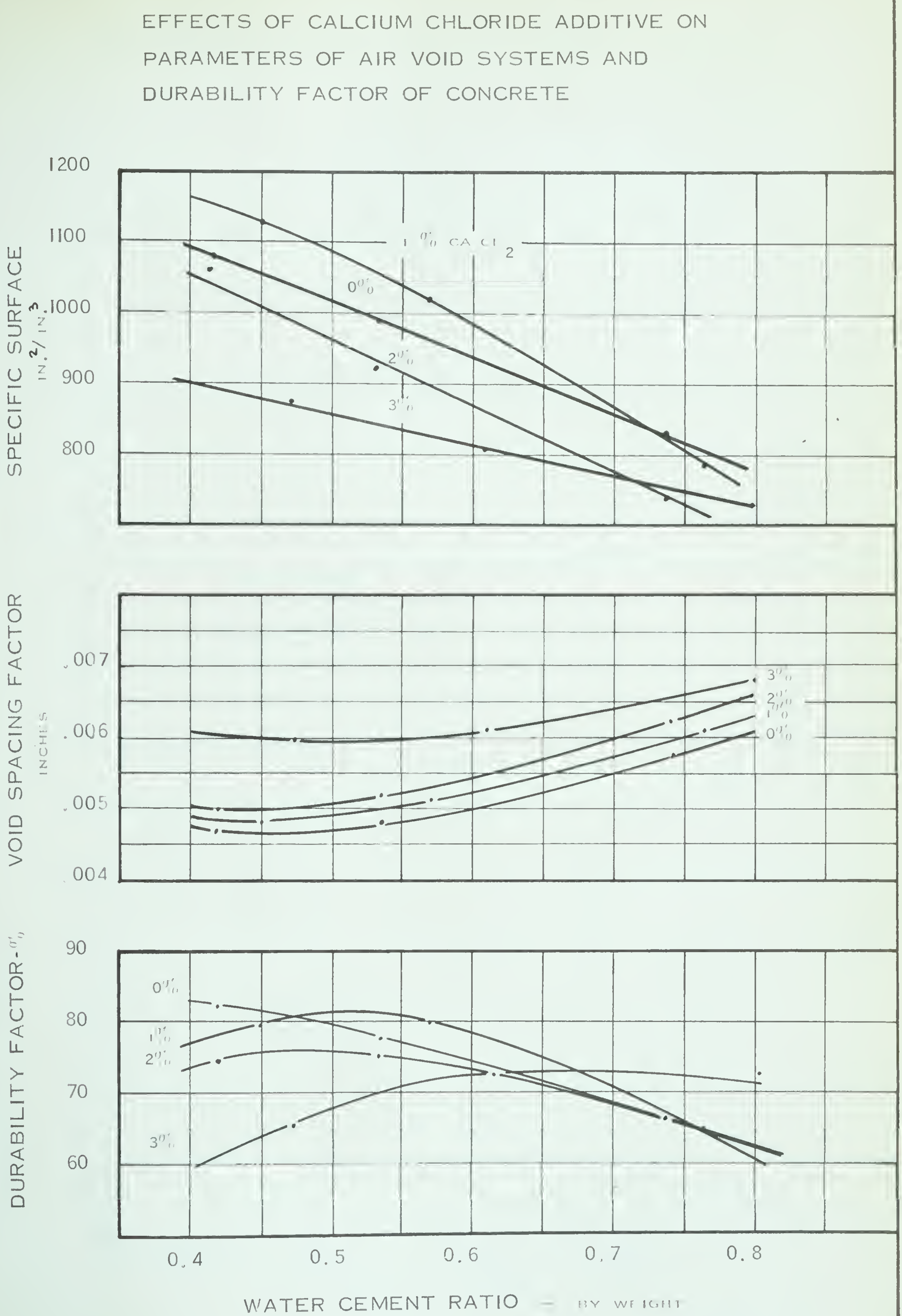

EFFECTS OF CALCIUM CHLORIDE ADDITIVE ON PARAMETERS OF AIR VOID SYSTEMS AND DURABILITY FACTOR OF CONCRETE
SPECIFIC SURFACE IN.2/IN.3
1200
1100
1000
900
800
1% CA Cl 2
0%
2%
3%
VOID SPACING FACTOR INCHES
.007
.006
.005
.004
3%
2%
1%
0%
DURABILITY FACTOR-%
90
80
70
60
0%
1%
2%
3%
0.4
0.5
0.6
0.7
0.8
WATER CEMENT RATIO — BY WEIGHT

FIGURE 16

RELATIONSHIP BETWEEN DURABILITY FACTOR WITH SPECIFIC SURFACE AND WITH SPACING FACTOR

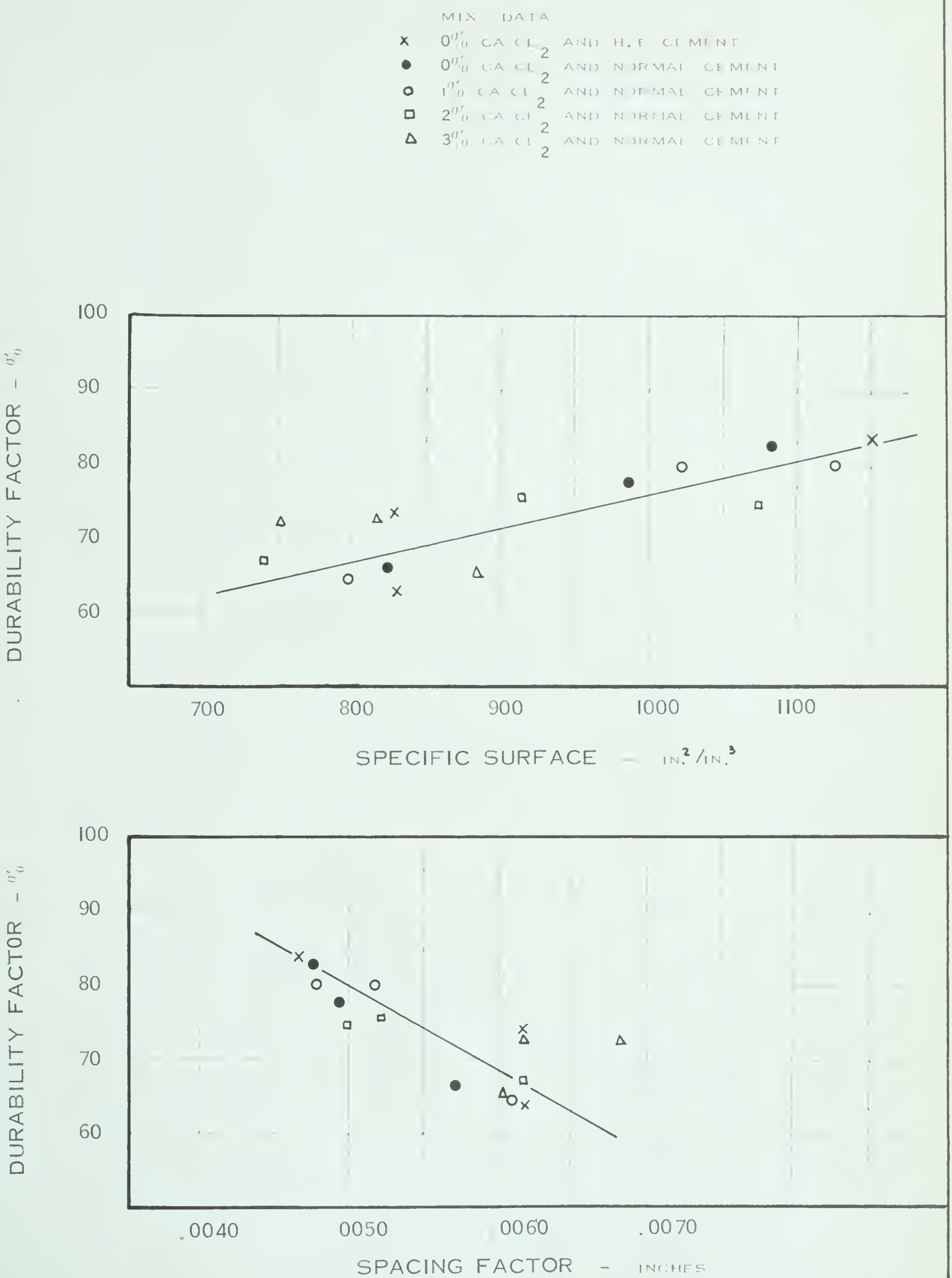


FIGURE 17

COMPARISON OF NORMAL PORTLAND CEMENT AND HIGH EARLY STRENGTH CEMENT IN REGARDS TO AIR VOID PARAMETERS AND DURABILITY FACTOR

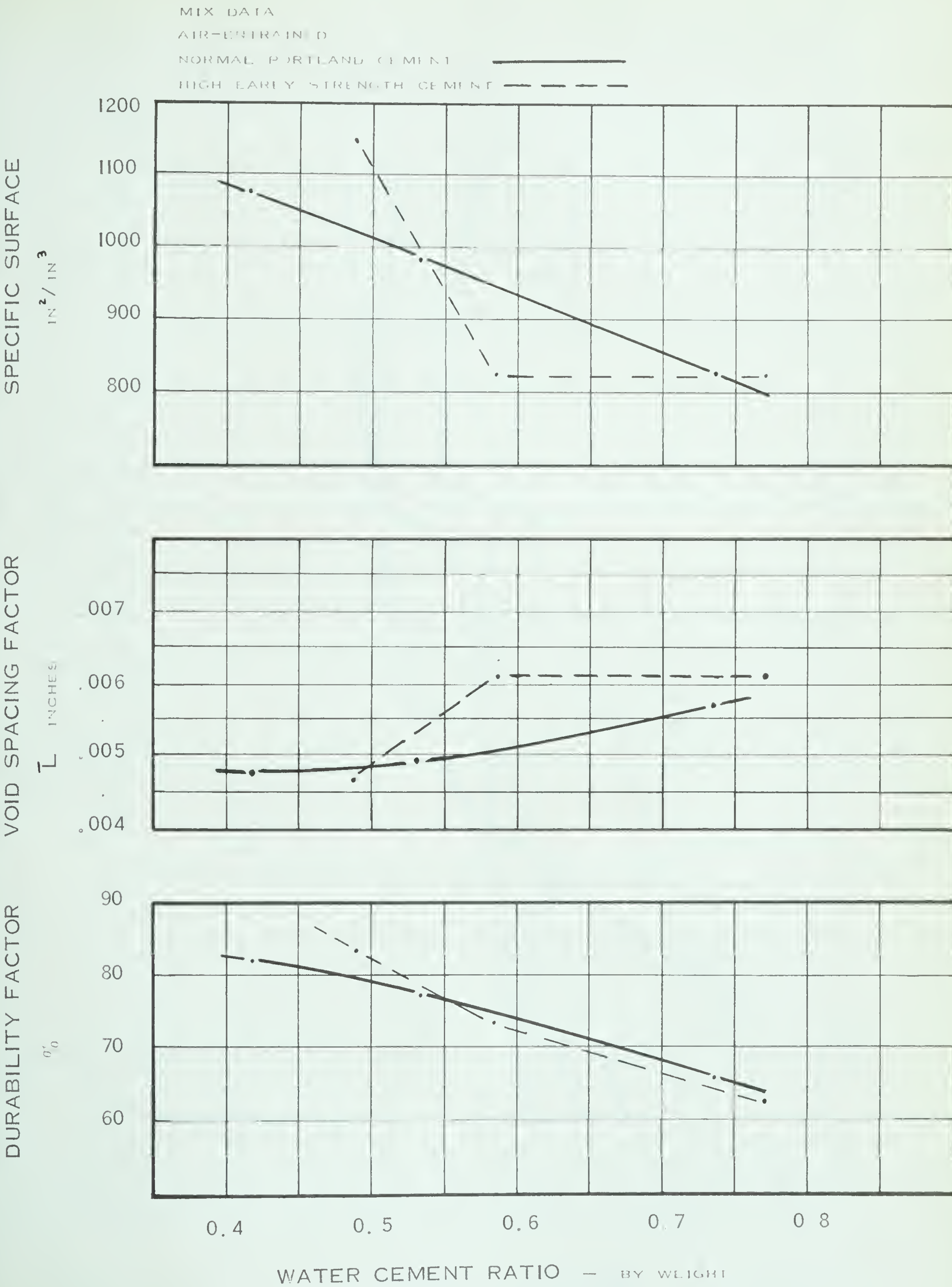


FIGURE 18

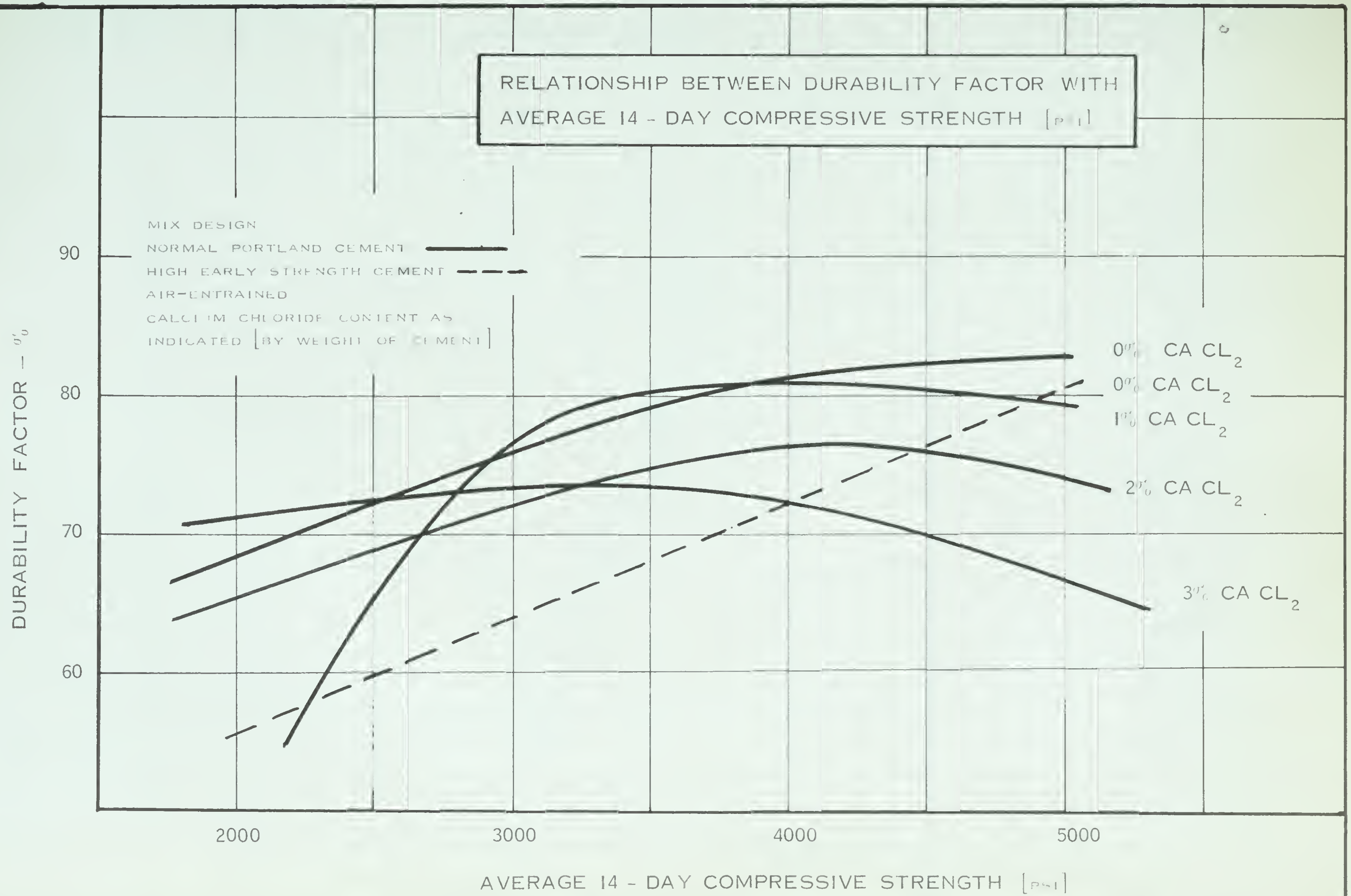

RELATIONSHIP BETWEEN DURABILITY FACTOR WITH
AVERAGE 14 - DAY COMPRESSIVE STRENGTH [PSI]
MIX DESIGN
NORMAL PORTLAND CEMENT
HIGH EARLY STRENGTH CEMENT
AIR-ENTRAINED
CALCIUM CHLORIDE CONTENT AS
INDICATED [BY WEIGHT OF CEMENT]
DURABILITY FACTOR – %
90
80
70
60
2000
3000
4000
5000
0% CA CL_2
0% CA CL_2
1% CA CL_2
2% CA CL_2
3% CA CL_2
AVERAGE 14 - DAY COMPRESSIVE STRENGTH [PSI]

FIGURE 19

RELATIONSHIP BETWEEN DURABILITY FACTOR WITH ADDITIONS OF CALCIUM CHLORIDE FOR CONSTANT 14-DAY COMPRESSIVE STRENGTH [psi]

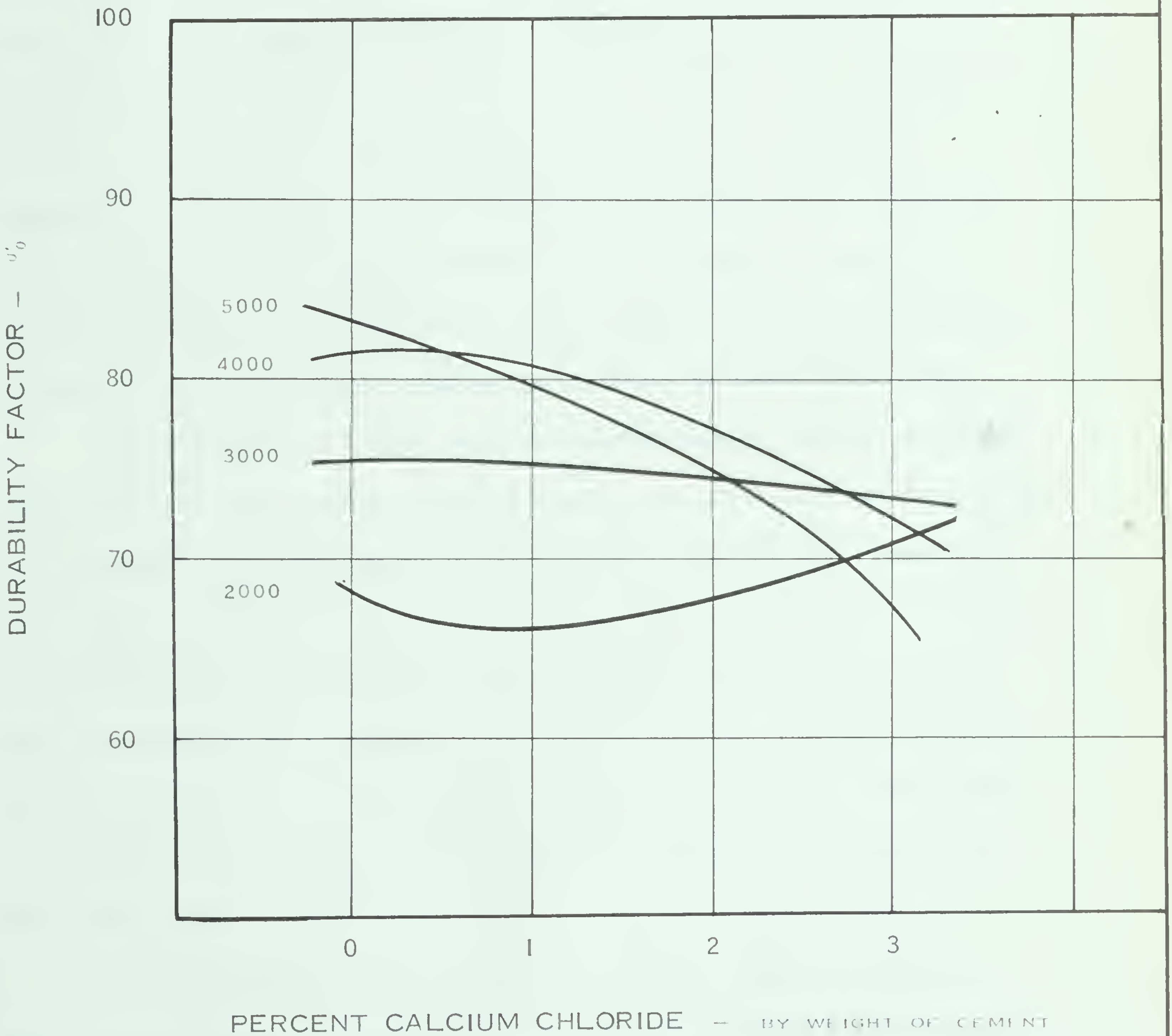


FIGURE 20

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5-1 CONCLUSIONS

The investigation reported above has shown that the freeze-thaw durability of concrete is dependent upon type of cement, water cement ratio, amount of calcium chloride admixture, and the effect of the calcium chloride admixture on the air void system of the concrete, as well as the effect of the calcium chloride on the amount of hydration of the cement. Other variable conditions such as age of testing, casting and curing temperatures, and quality of aggregate although of equal importance were kept constant in this investigation so that no conclusions are reached pertaining to these conditions.

The comparison of high early strength cement, normal portland cement and calcium chloride treated cement with freeze-thaw durability was dependent upon the amount of hydration of the cement. Additions of calcium chloride showed a greater accelerating effect on hydration at the high water cement ratio than at the low water cement ratios. This increased rate of hydration was illustrated by the gain in compressive strength of the calcium chloride treated concrete specimens, where the percentage gain in compressive strength was greater at the high water cement ratios than at the low water cement ratios.

Just as calcium chloride had a different effect at variable water cement ratios on compressive strength, it also had a different

effect for variable water cement ratios on durability factor. It appears that basically calcium chloride had a detrimental effect on the durability of concrete. However, at high water cement ratios, where the accelerating effects of calcium chloride are more pronounced, the detrimental effects of calcium chloride are offset. At the lower water cement ratio, the addition of calcium chloride had a less pronounced effect on hydration and consequently the durability factor decreased. This is illustrated aptly in FIGURE 13, where calcium chloride appears to be beneficial at the high water cement ratios but is definitely detrimental at the low water cement ratios.

This same argument applies to high early strength cement. Since high early strength cement has a greater rate of hydration than normal portland cement, it reaches a higher compressive strength at an earlier age. The increased amount of hydration of the high early strength concrete provides it with a freeze-thaw durability comparable to normal portland cement (at 14 days curing). Swenson (1955) stated that high early strength cement has a lower durability than normal portland cement on account of its greater fineness. When the durability of high early strength cement is compared to normal portland cement on the basis of comparable compressive strengths, there is a marked difference (FIGURE 19).

Since the amount of hydration of the cement plays such a prominent role on the freeze-thaw durability characteristics of

concrete, the durability factor should be compared to some other, more constant property of the concrete. Once concrete has set, the air void system incorporated throughout the concrete by air entrainment remains constant and provides a good basis for comparison. The current theoretical explanations of the action of entrained air in producing frost-resistant concrete show the importance of the size and distribution of the air voids. FIGURE 17 shows that specific surface and spacing factors are highly related to the durability factor.

The investigation of the effects of added calcium chloride on the air void parameters of concrete showed a definite detrimental effect, as the specific surface decreased and the void spacing factor increased. FIGURE 16 illustrates this and also it is apparent that at the lower water cement ratios, the detrimental aspects are more pronounced as the durability factor dropped 28.1% at a water cement ratio of 0.4.

The drop of 28.1% in durability is considerable enough to warrant some means of prevention. The author suggests that one possibility would be to specify calcium chloride content on some other basis than per cent weight of cement. As the water cement ratio decreases (cement content increases), the percentage of calcium chloride should be decreased. Therefore at a water cement ratio of 0.8, 3% calcium chloride may be acceptable, however as the water cement ratio decreases the calcium chloride content should also be

progressively decreased until at a water cement ratio of 0.4, it is reduced to only 1%.

A modification in specifying the amount of calcium chloride added should not present any problems since the principal reason for using calcium chloride in concrete is to produce early strength required to permit early removal of forms, or to provide protection against freezing. Concretes of low water cement ratio already have a higher early strength and higher heat generation than concretes of high water cement ratio so that the addition of calcium chloride is not as important.

An application of the findings in this investigation to field concrete is exceedingly difficult on account of the variable conditions encountered in the field. However the importance of the amount of hydration of cement on the durability of concrete has been illustrated. Therefore if field concrete is likely to receive freezing and thawing at an early age, calcium chloride can be added to accelerate the rate of hydration. However the amount of calcium chloride to be added depends upon the water cement ratio, and upon the effect of the calcium chloride on the air void parameters. The added calcium chloride should at no time change the air void parameters below the accepted standard to insure adequate durability. However more research is definitely needed to correlate the air void parameters required by actual freezing and thawing conditions encountered in the field.

5-2 RECOMMENDATIONS

The following recommendations are made as an aid for future research

pertaining to this field of study.

(1) It is recommended that any future research on freeze-thaw durability consider the amount of hydration of the cement. A program which would make the age at which the specimens are exposed to freeze-thaw conditions a variable would be extremely useful.

(2) From the literature reviewed, there are indications that the effect of added calcium chloride varies with the casting and curing temperatures. It is recommended that air void parameter studies should include the effects of casting and curing temperatures.

(3) It is recommended further that correlation of the air void parameters with the durability factor be studied. Variable air contents should be selected to provide a large range in results.

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APPENDIX A

SAMPLE DATA SHEETS

(1) Compressive Strength Testing

(2) Freeze-Thaw Testing

(3) Microscopic Analysis

UNIVERSITY OF ALBERTA PARTMENT OF CIVIL ENGINEERING CONCRETE LABORATORY	PROJECT Thesis DATE Dec. 13-14 '62 ENG.-TECH. F.M.

COMPRESSIVE STRENGTH OF CONCRETE CYLINDERS

DIAMETER 3.0 LENGTH 6.0 AREA 7.069

AGE OF TEST 28 DAY TEST

DESCRIPTION	NUMBER	MAX. LOAD POUNDS	AVE. MAX. LOAD LBS.	AVE. STRESS P.S.I.
N-400-0	1	16700		
	2	18400		
	3	16400		
	4	17950	17410	2410
N-550-0	1	21100		
	2	31100		
	3	31150		
	4	31650	30550	4330
N-700-0	1	42300		
	2	44200		
	3	42200		
	4	44600	43325	6140
6N-400-0	1	15900		
	2	14200		
	3	15700		
	4	13500	14825	2110
6N-550-0	1	27100		
	2	27000		
	3	27900		
	4	27100	27275	3860
6N-700-0	1	35100		
	2	35400		
	3	34600		
	4	36500	35400	5010

CONCRETE LABORATORY

Eng.-Technician P. M
Date STARTED DEC 28/62 @ 10:00 P.M.

Description of cement and aggregate: NORMAL PORTLAND CEMENT (N)
AIR ENTRAINED (6N) CALCIUM CHLORIDE ADDITIVE 1% – 2%
3/4" MAX SIZE AGGREGATE FROM DALE BROS SAND AND GRAVEL

BEAM DESCRIPTION

Date	No. of Cycles		1 6N-400-1 (1)	2 6N-400-1 (2)	3 6N-550-1 (1)	4 6N-550-1 (2)	5 6N-700-1 (1)	6 6N-700-1 (2)	7 6N-400-2 (1)	8 6N-400-2 (2)	9 6N-550-2 (1)	10 6N-550-2 (2)	11 6N-700-2 (1)	12 6N-700-2 (2)
DEC 28/62	0	FTF P_c -% 1/n²	1750 100 1/306	1770 100 1/313	1820 100 1/334	1810 100 1/331	1840 100 1/338	1840 100 1/338	1700 100 1/289	1730 100 1/299	1800 100 1/324	1800 100 1/324	1840 100 1/338	1850 100 1/342
DEC 30/62	21	FTF P_c	1640 880	1650 870	1710 875	1710 883	1750 907	1750 907	1600 885	1600 865	1650 840	1670 96.1	1760 917	1750 895
JAN 2/63	56	FTF P	1600 836	1610 828	1710 875	1710 883	1740 896	1740 896	1580 864	1590 845	1650 840	1670 96.1	1750 905	1740 885
JAN 5/63	91	FTF P_c	1600 836	1610 82.8	1700 868	1700 875	1720 875	1740 896	1570 853	1570 825	1640 831	1640 93.1	1720 818	1730 878
JAN 8/63	124	FTF P	1600 836	1590 810	1700 868	1680 852	1710 863	1720 874	1530 811	1520 772	1600 790	[illegible] 83.1	1700 855	1710 855
JAN 11/63	161	FTF P_c	1600 836	1540 760	1690 859	1660 830	1100 858	1710 86.5	1490 770	1500 153	1600 790	1630 92.1	1690 845	1700 845
JAN 15/63	207	FTF P_c	1560 793	1500 720	1690 859	1650 823	1690 845	1680 833	1400 679	1480 732	1580 711	1620 810	1670 822	1660 805
JAN 21/63	263	FTF P_c	1510 74.2	1430 652	1680 844	1640 811	1670 825	1660 81.2	1400 679	1460 713	1580 77.1	1600 79.0	1670 82.2	1620 76.9

CONCRETE LABORATORY

Technician: [illegible]

STARTED: [illegible]

Description of [illegible]

[illegible] DESCRIPTION

Date	[illegible]		6H-400 -1	6H-400 -1	6H-550 -1	6H-550 -1	6H-700 -1	6H-700 -1	6H-400 -2	6H-400 -2	6H-550 -2	6H-550 -2	6H-700 -2	6H-700 -2
JAN 24 [illegible]	300	F P	1450 686	1380 608	1650 815	[illegible] 784	1640 795	1650 805	1480 658	1450 684	1540 732	1580 770	1640 795	1550 685
		F P												
D.F. = $\frac{P.N.}{M.}$		F P												
M = 300 N = CYCLES @ 60%		F P												
DURABILITY FACTOR		F P	686	608	815	784	795	805	658	684	732	770	795	685
AVERAGE DURABILITY FACTOR			647		799		800		67.1		75.1		73.[illegible]	
		F P												
		F P												
		F P												

[illegible]
[illegible]
[illegible]

REPORT: THESIS
DATE: JAN [illegible], 1963
[illegible] ENG.: E M

MICROSCOPICAL DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. CM-[illegible] - [illegible] 3½ x 4½ x 16" SOURCE: 3½ 4½ 16 BEAM

W/C = 0.758, DF = 66.1, 3/4" MAX [illegible] AGGREGATE

LINEAR TRAVERSE METHOD

Revolution No.	N	Ru	Rm	Revolution No.	N	Ru	Rm
1	34	31	80	13	514	492	1040
2	75	81	160	14	554	528	1120
3	115	102	240	15	594	564	1200
4	156	161	320	16	629	613	1280
5	198	193	400	17	662	646	1358
6	236	226	480	18	700	682	1440
7	259	246	560	19	738	713	1520
8	297	278	640	20	779	764	1600
9	347	354	719	21	843	828	1680
10	381	379	800	22	915	887	1759
11	418	412	880	23	941	911	1800
12	464	454	960				

l = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pd = [illegible] the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = [illegible] in inches per revolution
Rm = total number of revolutions of the [illegible] screw
n = [illegible] air voids [illegible] per inch
α = specific surface
L̄ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$l = \frac{Pu\,Ru}{N} = \frac{1}{20} \cdot \frac{911}{941} = 0.00486$	$\bar{L} = \frac{P}{400\,n}$ $\quad (\frac{P}{A} < 4.33)$
$T = Pu\,Ru + Pm\,Rm = \frac{1}{20}(911 + 1800) = 94.56$	
$n = \frac{N}{T} = \frac{941}{94.56} = 9.95$	$\bar{L} = \frac{3}{\alpha}\left[1.4\left(\frac{P}{A}+1\right)^{1/3} - 1\right] \quad (\frac{P}{A} > 4.33)$
$A = 100\,n\,l = 100 \times 9.95 \times .00486 = 4.84\%$	$= \frac{3}{824}\left[1.4\,(6.15)^{1/3} - 1\right]$
$\alpha = \frac{4}{l} = 4/.00486 = 824$ sq in/in³	$= \frac{3}{824}(2.57 - 1)$
$P = 0.249 \quad P/A = \frac{24.9}{4.84} = 5.15$	$= \frac{3}{824} \times 1.57 = 0.00512$

APPENDIX B

FREEZE-THAW DURABILITY RESULTS

UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
CONCRETE DURABILITY TEST

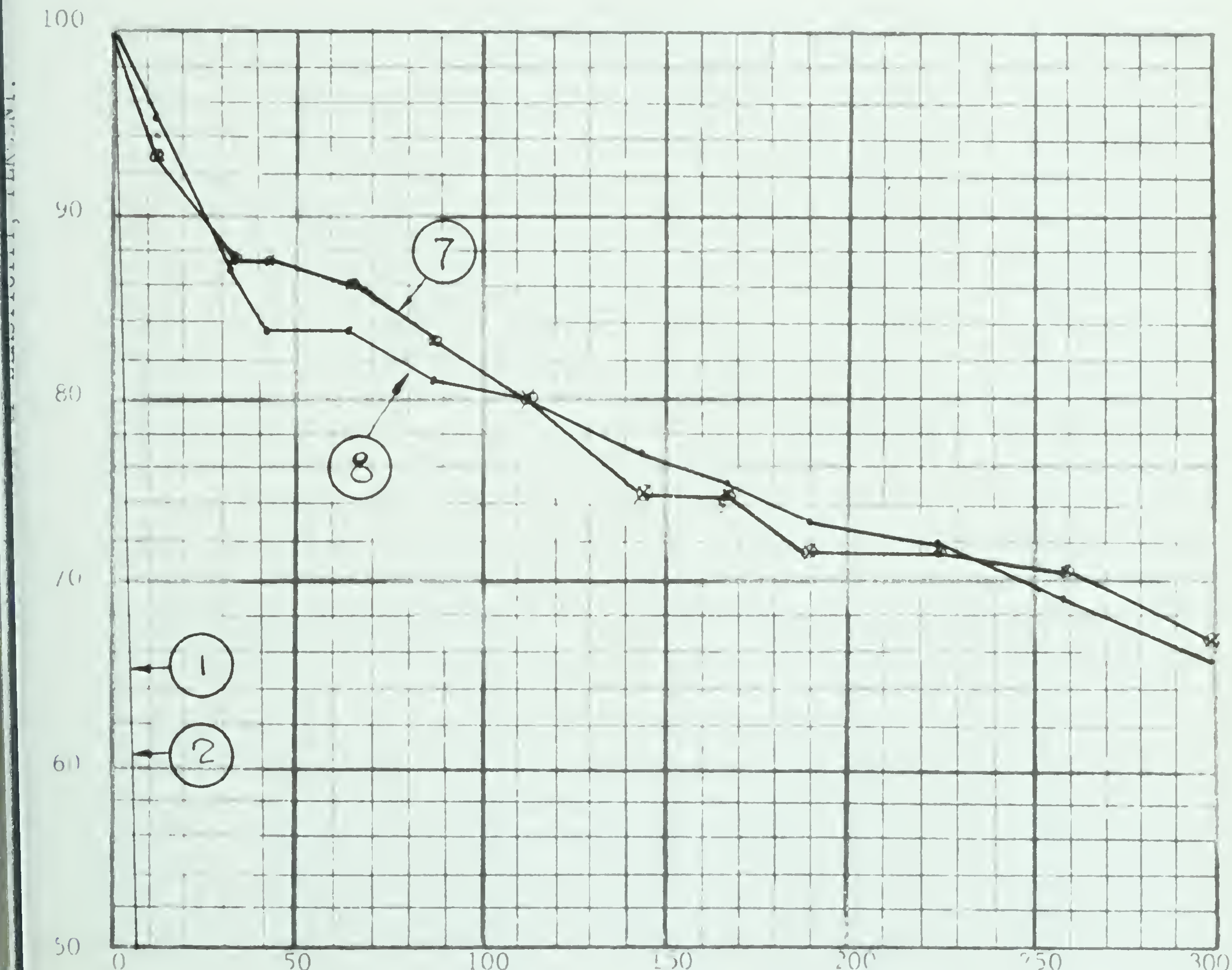
Proj... THESIS
Date DEC 27 /62
Eng. P.M.

...e Aggre... F.M. - 2.69
...rse Aggregate 3/4" MAX
...ment NORMAL PORTLAND
...ture NONE ADDED
- NON AIR ENTRAINED GN - AIR

M... IMMERSED IN SAT LIME SOLUTION @ 70°F ± 3°F
[illegible] 14 DAYS
Beam Temp. Range 0° - 40°F

Symbol or w/c	Air Content	Slump	Weight 0 Cycles GMS	Weight, end of test	Durability	Visual Inspection
N-400-0	0.90%	3 1/4"	9637	9095	1	SEE
N-400-0	"	"	9663	9450	1	PHOTOGRAPHS
GN-400-0	6.0%	3.0"	9410	8581	66.4	
GN-400-0	"	"	9286	8724	65.8	

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING



TWO HOUR CYCLES OF FREEZING AND THAWING

UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
CONCRETE DURABILITY TEST

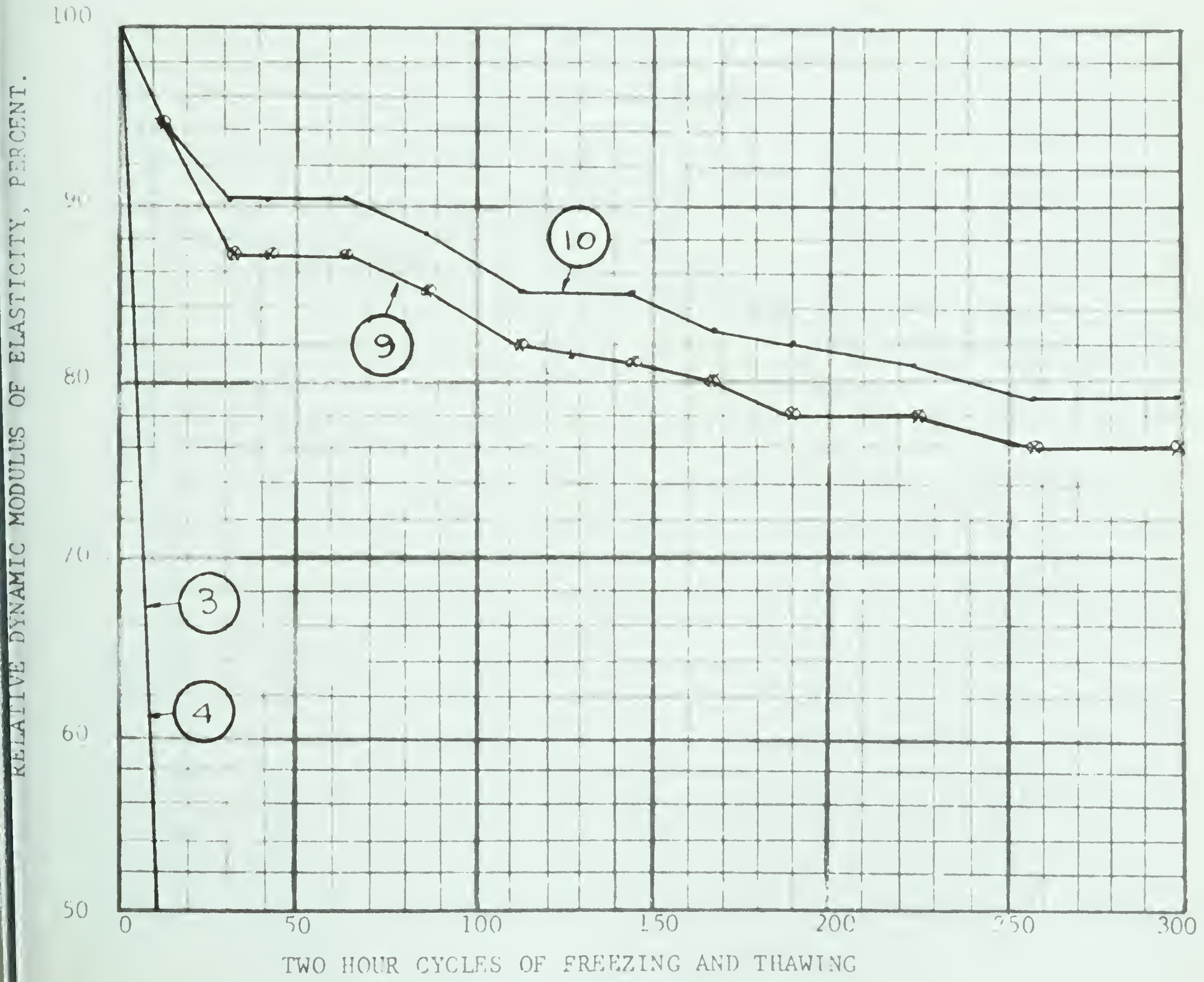
THESIS
DEC 27/62
PM

ine Aggregate F M 2.69
oarse Aggregate 3/4" MAX
ement NORMAL PORTLAND
dmixture NONE ADDED

IMMERSED IN SAT. LIME SOLUTION @ 70° ± 3° F
Age at test 14 DAYS
Beam Temp. Range 0° – 40° F

Number	Air Content	Slump	Weight of Cycles	Weight, end of test	Durability Factor	Visual Inspection
N-550-0	1.40%	3.0"	9801	9855	1.6	SEE
N-550-0	"	"	9766	9805	1.6	PHOTOGRAPHS
6N-550-0	5.7%	2 3/4"	9568	9259	76.0	
6N-550-0	"	"	9518	9199	79.0	

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING



UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
CONCRETE DURABILITY TEST

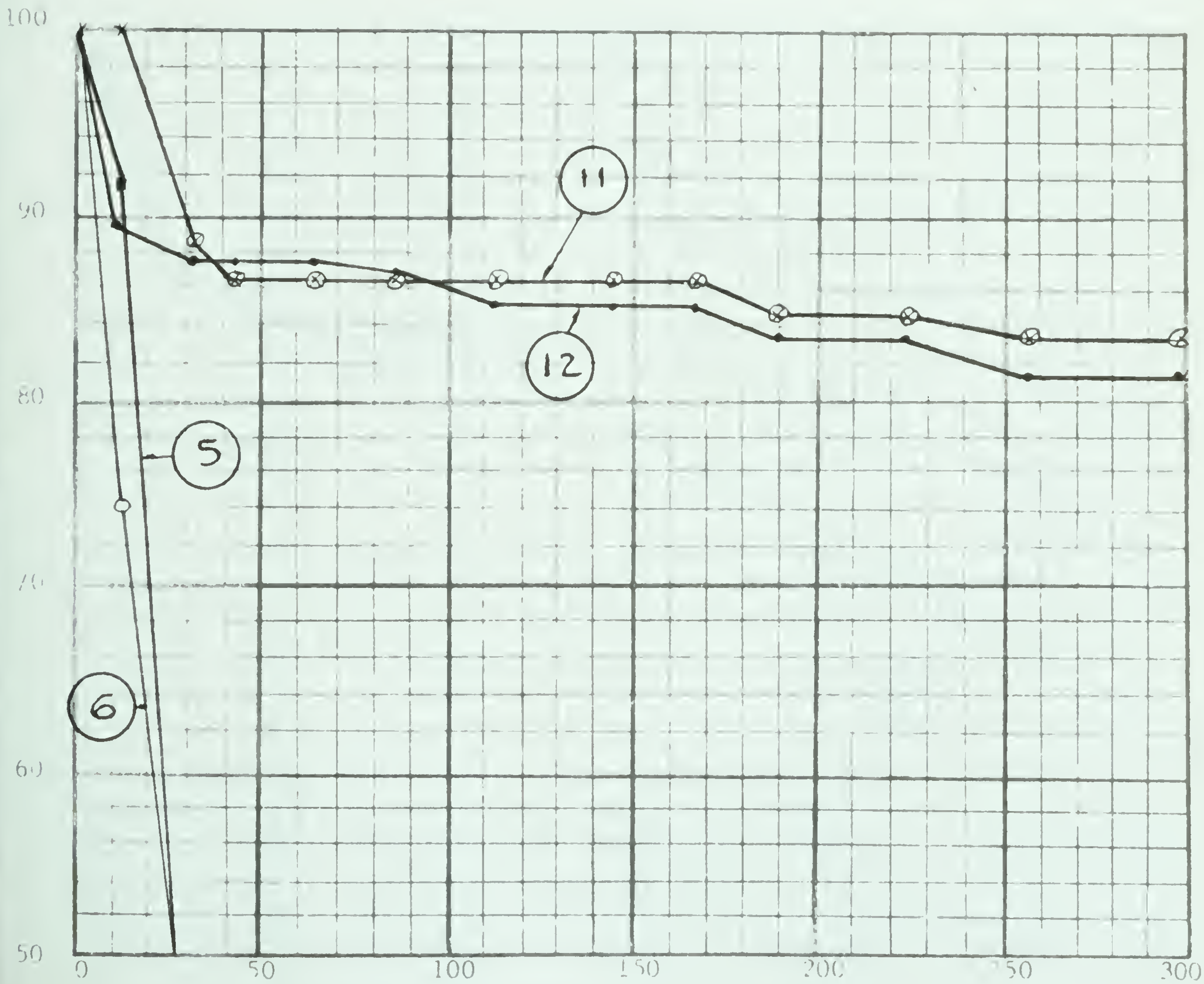
Project THESIS
Date DEC 27/62
Eng.-Tech. D.M.

...ne Aggregate F.M 2.69
...arse Aggregate 3/4" MAX. SIZE
...ment NORMAL PORTLAND
...mixture NONE ADDED

Method of curing IMMERSED IN SAT. LIME SOLUTION @ 70° ± 3°F
Age at test 14 DAYS
Beam Temp. Range 0° - 40°F.

...	Air Content	Slump	W...	W...	Durability Factor	Visual Inspection
N-700-0	1.3 %	3¼"	10135	10145	14.4	SEE
N-700-0	"	"	10037	10062	13.2	PHOTOGRAPHS
6N-700-0	6.0 %	3.0"	9690	9480	83.5	
6N-700-0	"	"	9640	9425	81.5	

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING



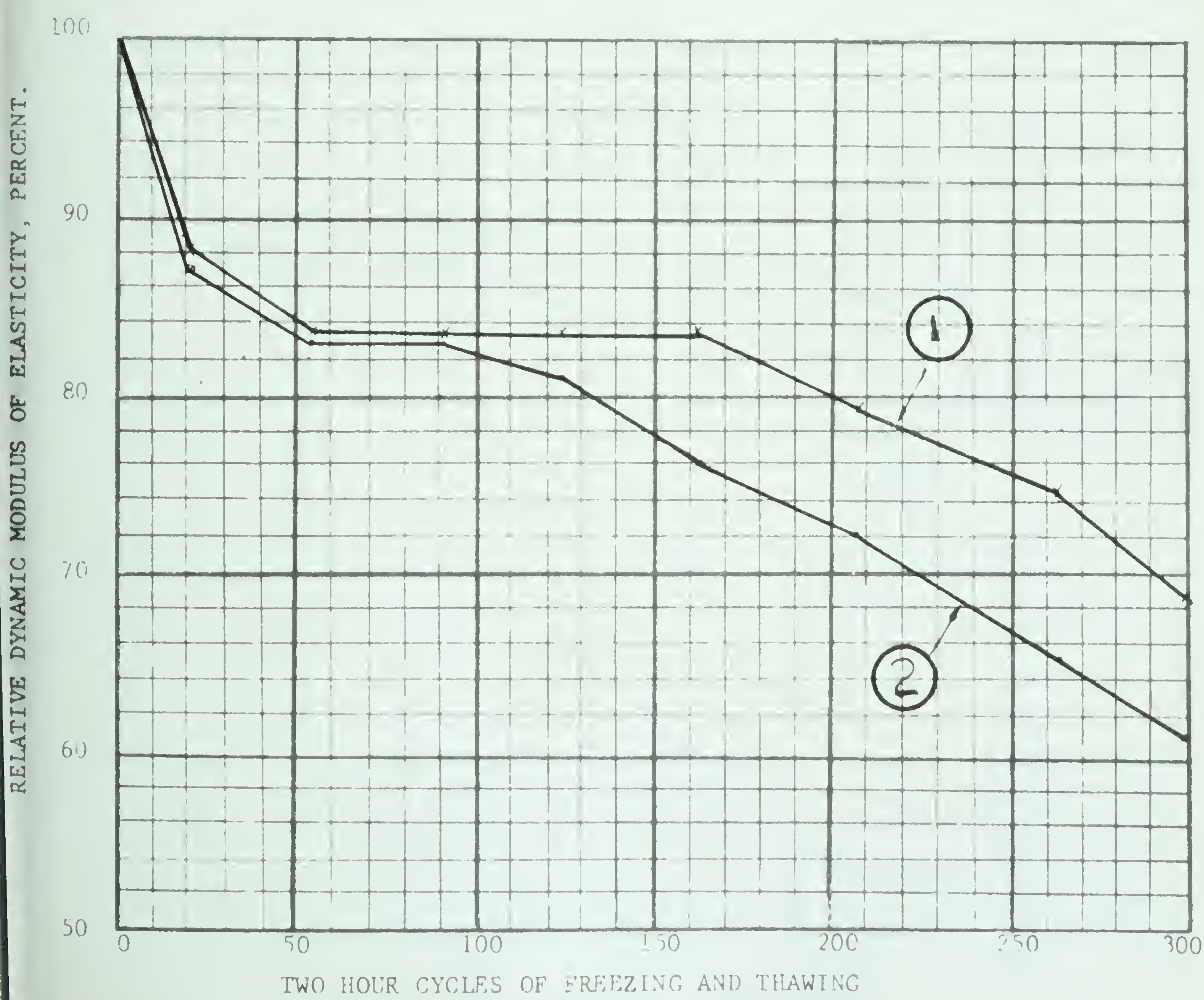
TWO HOUR CYCLES OF FREEZING AND THAWING

UNIVERSITY OF ALBERTA DEPARTMENT OF CIVIL ENGINEERING CONCRETE DURABILITY TEST	Project THESIS Date JAN 24/63 Eng.-Tech. P. M.

Fine Aggregate FM = 2.69 Coarse Aggregate 3/4" MAX Cement NORMAL PORTLAND Admixture CALCIUM CHLORIDE - 1% - 2% AIR ENTRAINED	Method of curing IMMERSED IN SAT LIME SOLUTION @ 70 °F ± 3° Age at test 14 DAYS Beam Temp. Range 0° - 40°F

Symbol or w/c	Air Content	Slump	Weight 0 Cycles	Weight, end of test	Durability Factor	Visual Inspection
6N-Acc-1	5.7 %	2 3/4"	9597	9229	68.6	SEE PHOTOGRAPHS
6N-Acc-1		"	9638	9266	60.8	"

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING



UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
CONCRETE DURABILITY TEST

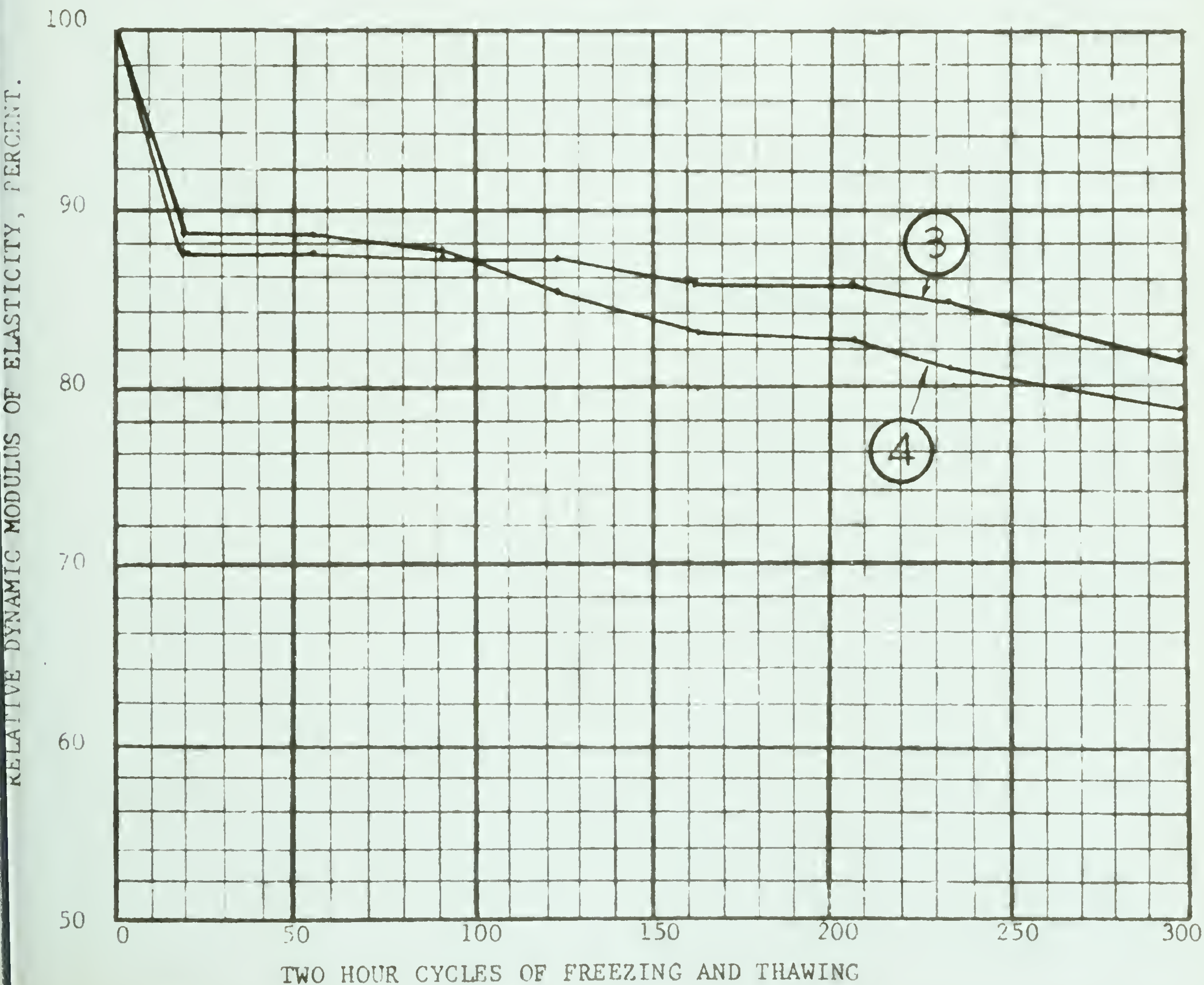
Project THESIS
Date JAN. 24/63
Eng.-Tech. PM

Fine Aggregate FM = 2.69
Coarse Aggregate 3/4" MAX.
Cement NORMAL PORTLAND
Admixture CALCIUM CHLORIDE 1%
AIR ENTRAINED

Method of curing IMMERSED IN SAT LIME SOLUTION @ 70±3°F
Age at test 14 DAYS
Beam Temp. Range 0-40°F.

Symbol or w/c	Air Content	Slump	Weight 0 Cycles	Weight, end of test	Durability Factor	Visual Inspection
6N-550-1	5.7%	3.0"	9537	9335	81.5	SEE PHOTOGRAPHS
6N-550-1	"	"	9556	9355	78.4	

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING

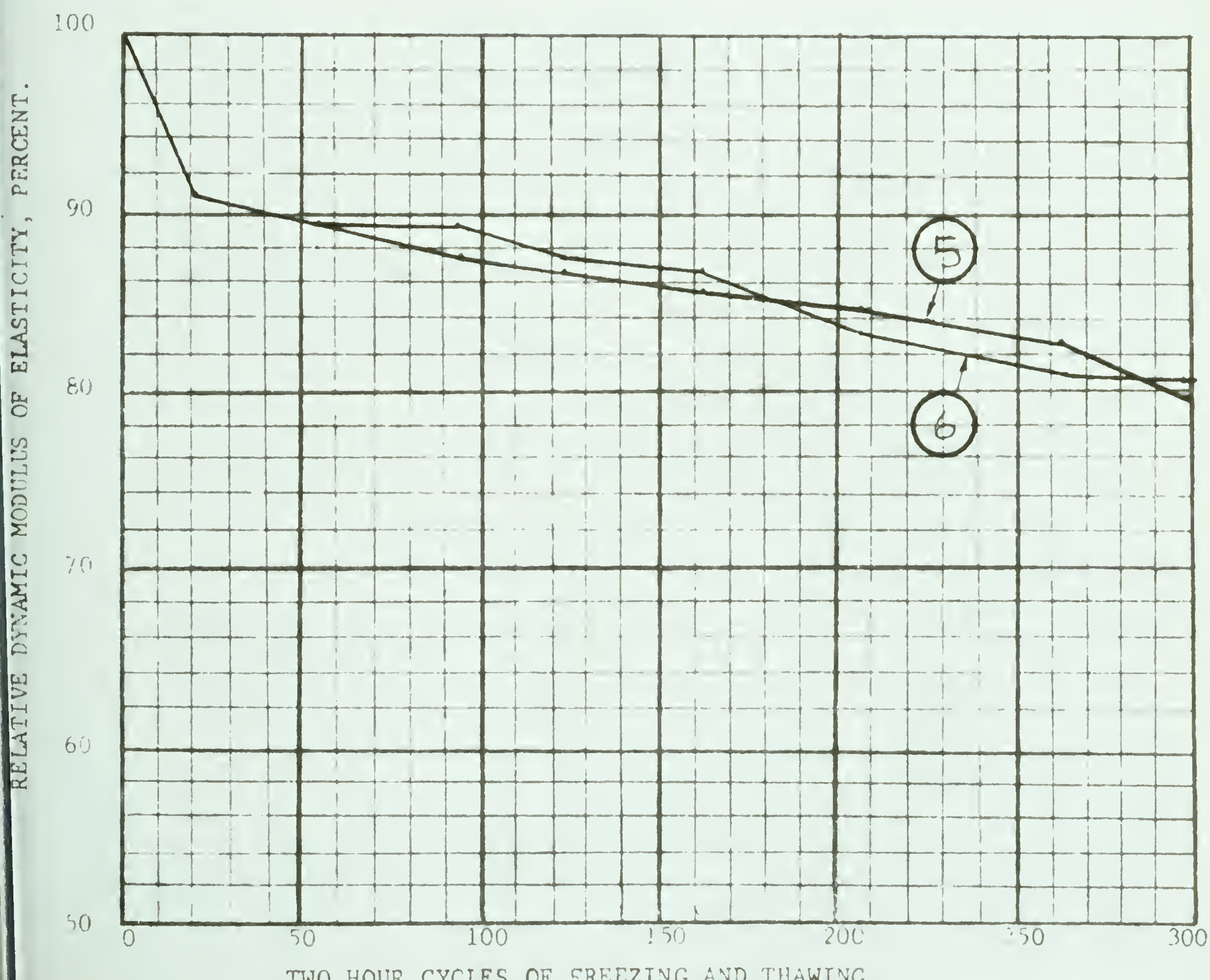


UNIVERSITY OF ALBERTA DEPARTMENT OF CIVIL ENGINEERING CONCRETE DURABILITY TEST	Project THESIS Date JAN 24/63 Eng.-Tech. P.M.

Fine Aggregate F.M. = 2.69 Coarse Aggregate 3/4" MAX. Cement NORMAL PORTLAND Admixture CALCIUM CHLORIDE 1% AIR ENTRAINED	Method of curing IMMERSED IN SAT LIME SOLUTION @ 70±3°F Age at test 14 DAYS Beam Temp. Range 0-40°F.

Symbol or w/c	Air Content	Slump	Weight 0 Cycles	Weight, end of test	Durability Factor	Visual Inspection
6N-700-1	5.6%	3 1/4"	9570	9472	79.5	SEE PHOTOGRAPHS
6N-700-1	"	3 1/4"	9530	9430	80.5	"

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING

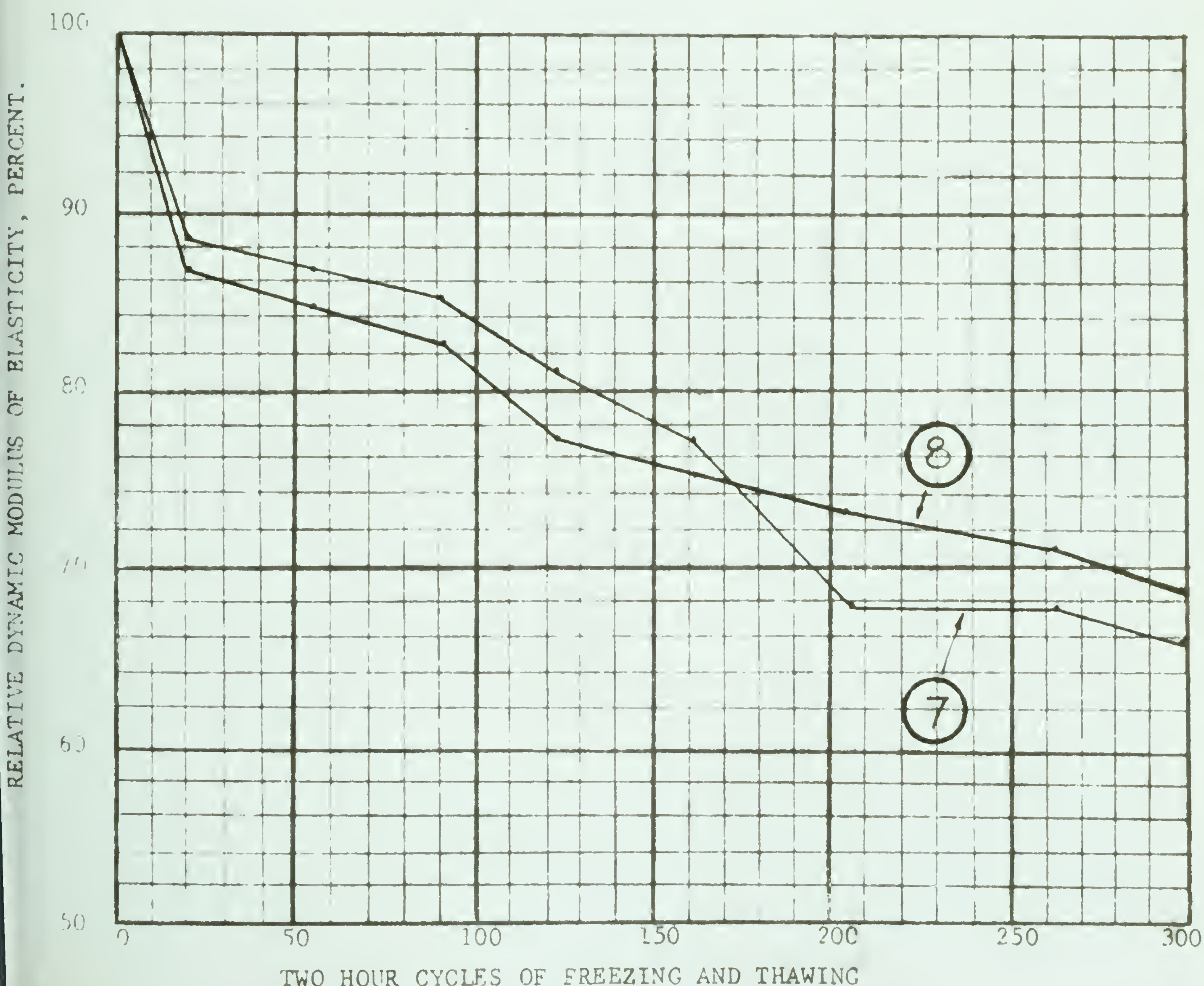


UNIVERSITY OF ALBERTA DEPARTMENT OF CIVIL ENGINEERING CONCRETE DURABILITY TEST	Project THESIS Date JAN. 24/63 Eng.-Tech. P.M.

Fine Aggregate F M = 2.69 Coarse Aggregate 3/4" MAX. Cement NORMAL PORTLAND Admixture CALCIUM CHLORIDE - 2% AIR ENTRAINED	Method of curing IMMERSED IN SAT. LIME SOLUTION @ 70±3°F Age at test 14 DAYS Beam Temp. Range 0-40°F

n	Symbol or w/c	Air Content	Slump	Weight o Cycles	Weight, end of test	Durability Factor	Visual Inspection
	6N-400-2	5.9%	3.0	9315	8912	65.8	SEE PHOTOGRAPHS
	6N-400-2	"	"	9460	9062	68.4	"

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING

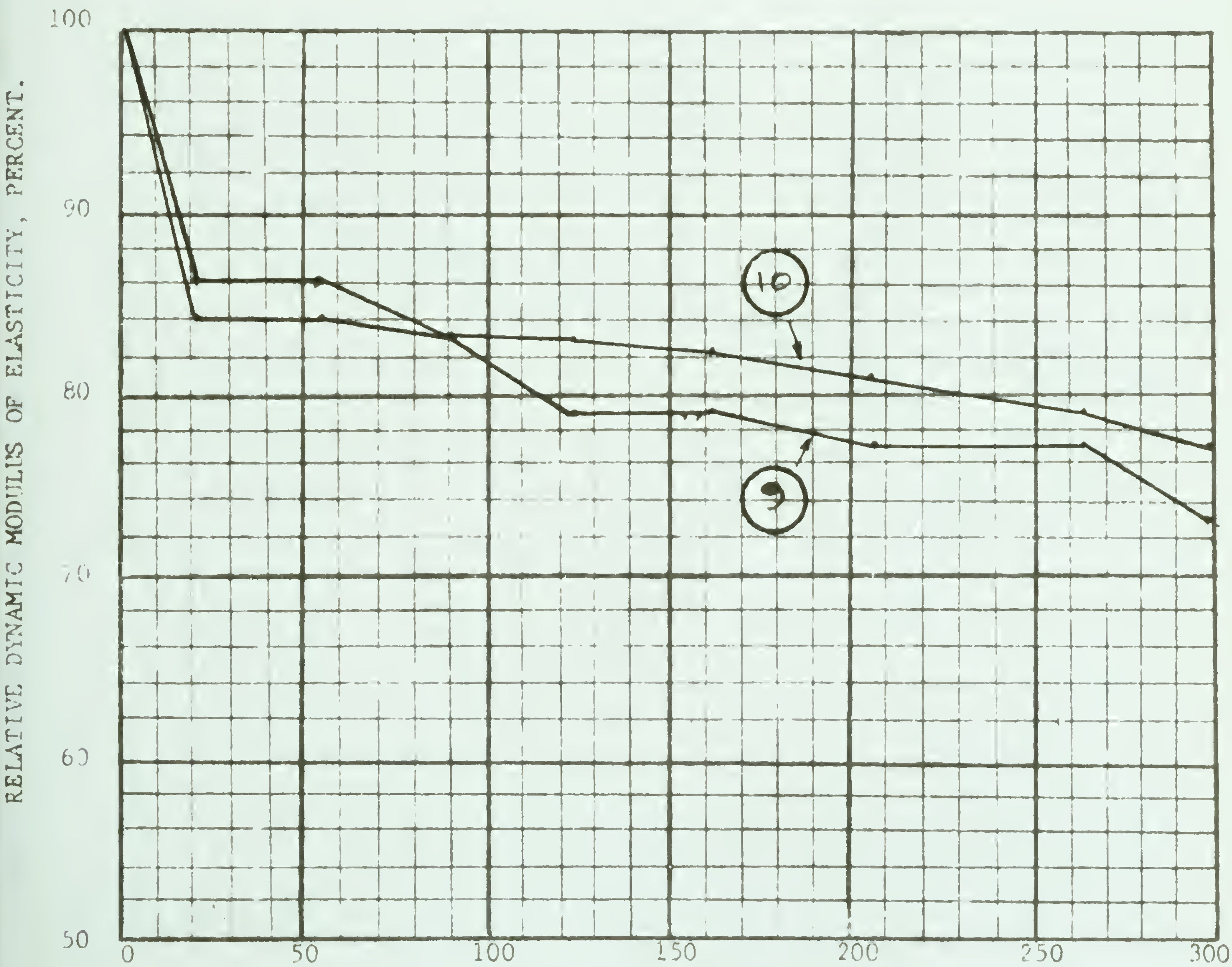


UNIVERSITY OF ALBERTA DEPARTMENT OF CIVIL ENGINEERING CONCRETE DURABILITY TEST	Project THESIS Date JAN. 24/63 Eng.-Tech. P.M.

Fine Aggregate F.M. = 2.69 Coarse Aggregate 3/4" MAX. Cement NORMAL PORTLAND Admixture CALCIUM CHLORIDE 2% AIR ENTRAINED	Method of curing IMMERSED IN SAT LIME SOLUTION @ 70±3°F Age at test 14 DAYS Beam Temp. Range 0 - 40°F.

Symbol or w/c	Air Content	Slump	Weight 0 Cycles	Weight, end of test	Durability Factor	Visual Inspection
6N-550-2	6.0%	3½"	9402	9155	732	SEE PHOTOGRAPHS.
6N-550-2	"	"	9605	9380	770	"

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING

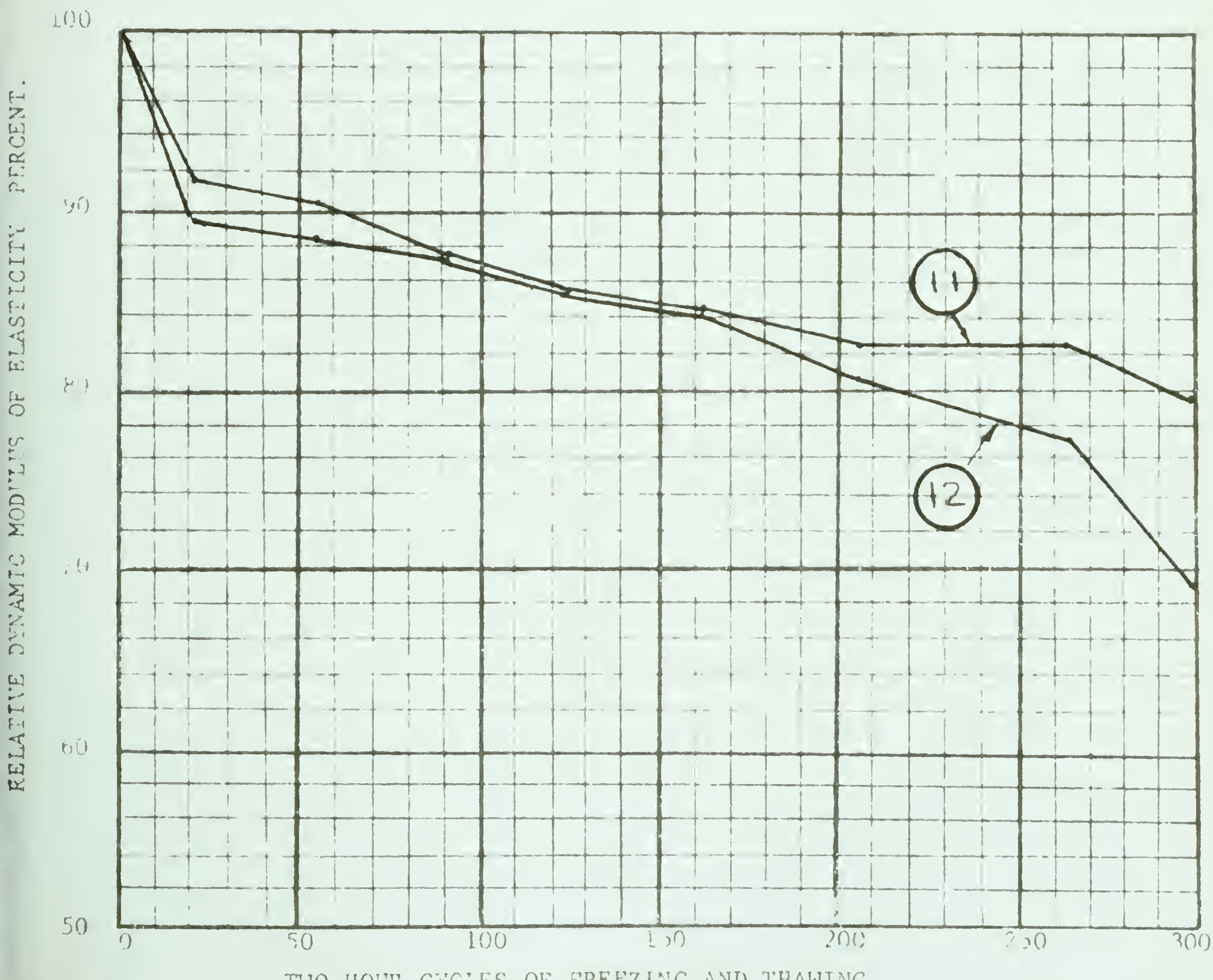


UNIVERSITY OF ALBERTA DEPARTMENT OF CIVIL ENGINEERING CONCRETE DURABILITY TEST	Project THESIS Date JAN. 24/63 Eng.-Tech. P. M.

Fine Aggregate F.M. = 2.69 Coarse Aggregate 3/4" MAX. Cement NORMAL PORTLAND Admixture CALCIUM CHLORIDE 2% AIR ENTRAINED	Method of curing IMMERSED IN SAT. LIME SOLUTION @ 70±3°F Age at test 14 DAYS Beam Temp. Range 0 - 40°F

m	Symbol or w/c	Air Content	Slump	Weight o Cycles	Weight, end of test	Durability Factor	Visual Inspection
	6N-700-2	5.5%	3½"	9650	9561	79.5	SEE PHOTOGRAPHS
2	6N-700-2	"	"	9560	9484	68.5	"

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING



UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
CONCRETE DURABILITY TEST

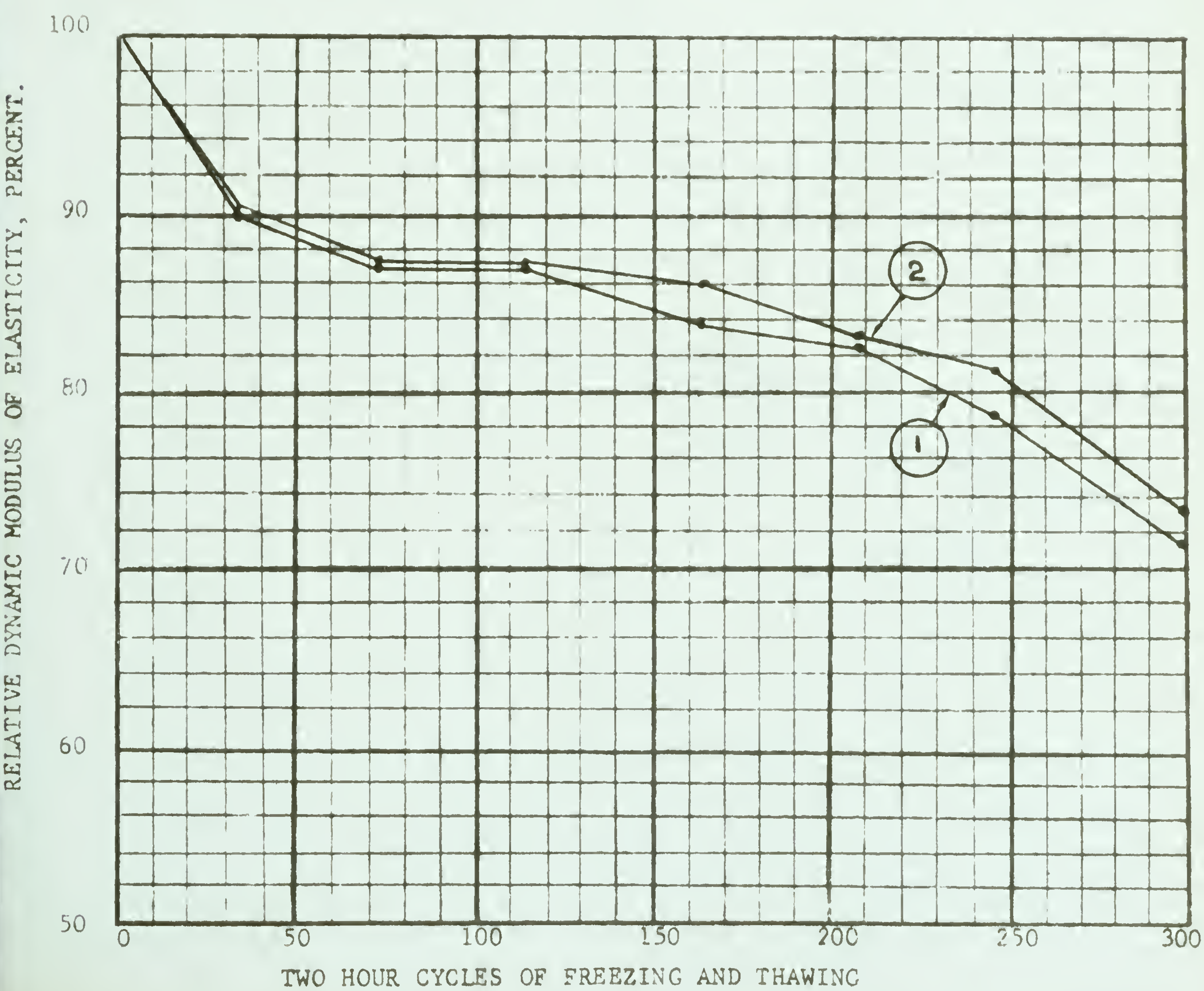
Project THESIS
Date FEB 24 '63
Eng.-Tech. P.M

Fine Aggregate F.M. 2.69
Coarse Aggregate 3/4" MAX.
Cement NORMAL PORTLAND
Admixture CALCIUM CHLORIDE - 3% AIR ENTRAINED.

Method of curing IMMERSED IN SAT. LIME SOLUTION AT 70°±3 F.
Age at test 14 DAYS
Beam Temp. Range 0° - 40° F

Symbol or w/c	Air Content	Slump	Weight 0 Cycles	Weight, end of test	Durability Factor	Visual Inspection
6N-400-3	5.7%	3.0	9569	9162	71.5	SEE PHOTOGRAPHS
6N-400-3			9575	9165	73.7	

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING



UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
CONCRETE DURABILITY TEST

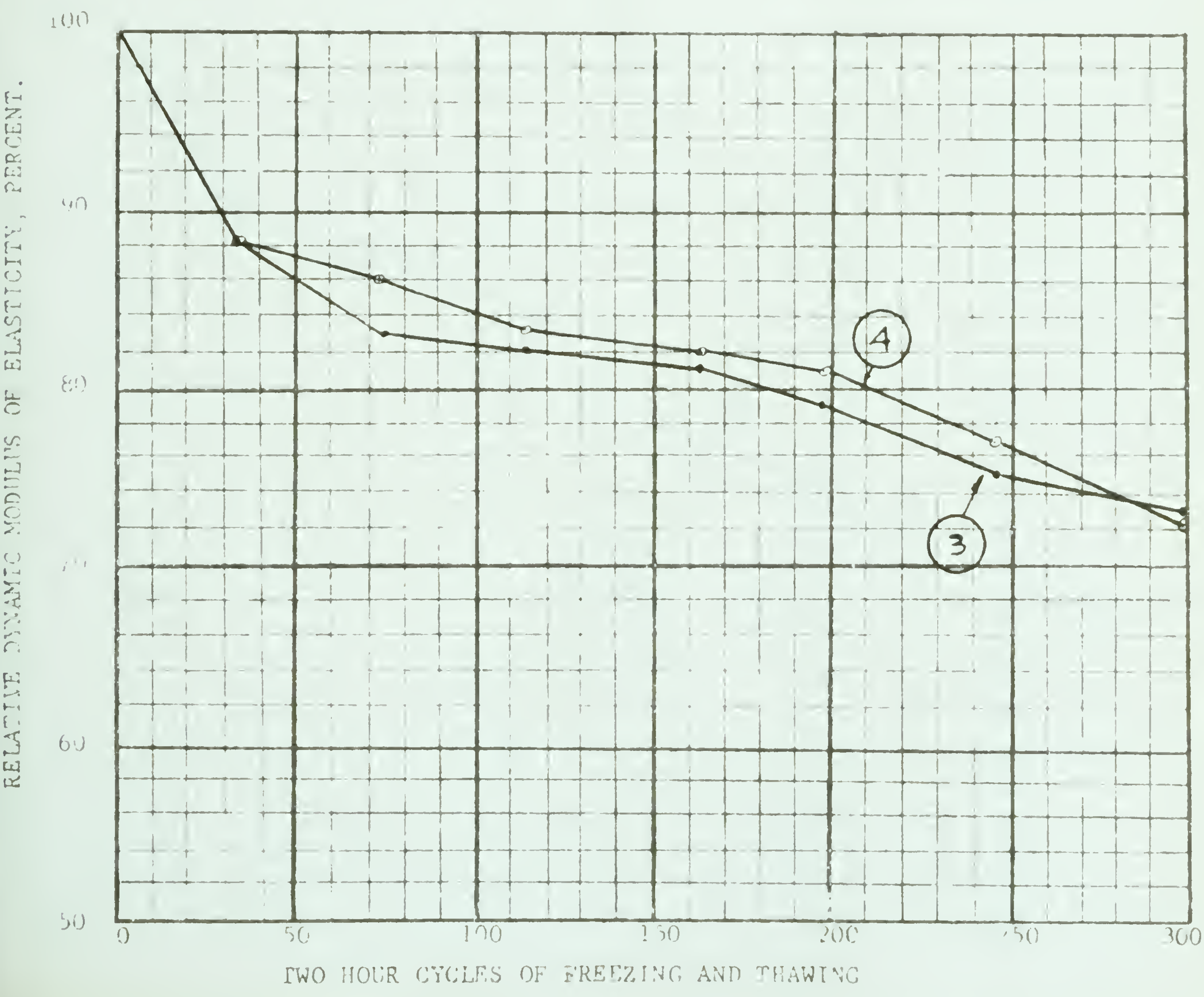
Project: THESIS
Date: FEB 24/63
Eng.-Tech.: F.M.

Fine Aggregate: F.M. = 2.69
Coarse Aggregate: 3/4" MAX
Cement: NORMAL PORTLAND
Admixture: CALCIUM CHLORIDE 3%, AIR ENTRAINED

Method of curing: IMMERSED IN SAT. LIME SOLUTION AT 70 ± 3° F
Age at test: 14 DAYS
Beam Temp. Range: 0° - 40° F

Bm. No.	Symbol or w/c	Air Content	Slump	Weight 0 Cycle	Weight, end of test	Durability Factor	Visual Inspection
	6N-550-3	6.0	3½	9650	9347	73.2	SEE PHOTOGRAPHS
	6N-550-3			9502	9197	72.2	

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING



UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
CONCRETE DURABILITY TEST

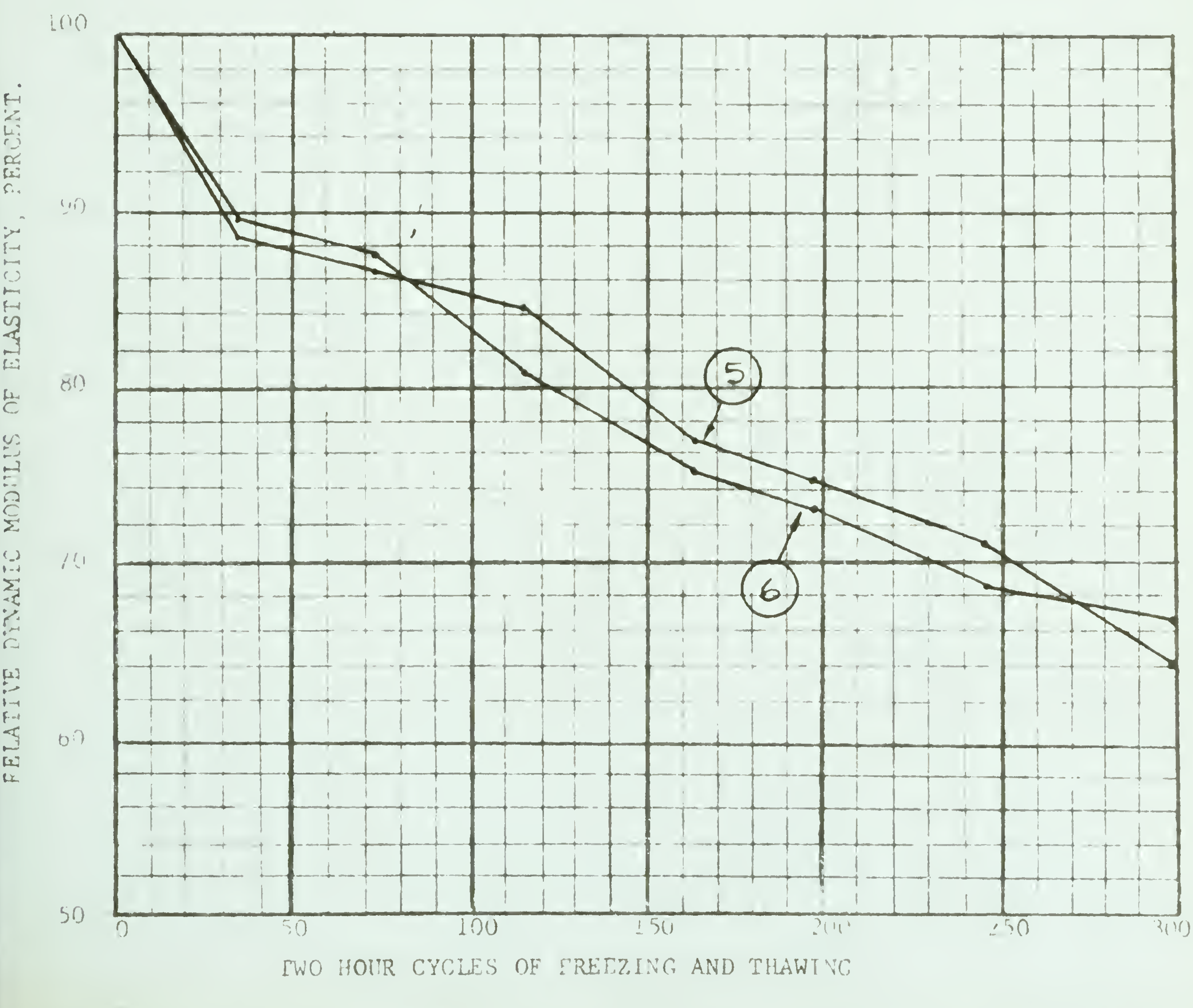
Project THESIS
Date FEB. 24 /63
Eng.-Tech. P.M.

Fine Aggregate F M = 2.69
Coarse Aggregate 3/4" MAX SIZE
Cement NORMAL PORTLAND
Admixture CALCIUM CHLORIDE - 3%
AIR ENTRAINED

Method of curing IMMERSED IN SAT LIME SOLUTION @ 70 ± 3° F
Age at test 14 DAYS
Beam Temp. Range 0° - 40°F

Symbol or w/c	Air Content	Slump	Weight 0 Cycles	Weight, end of test	Durability Factor	Visual Inspection
6H-700-3	6.2	3½	9545	9361	64.0	SEE PHOTOGRAPHS
6N-700-3			9558	9388	66.5	

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING

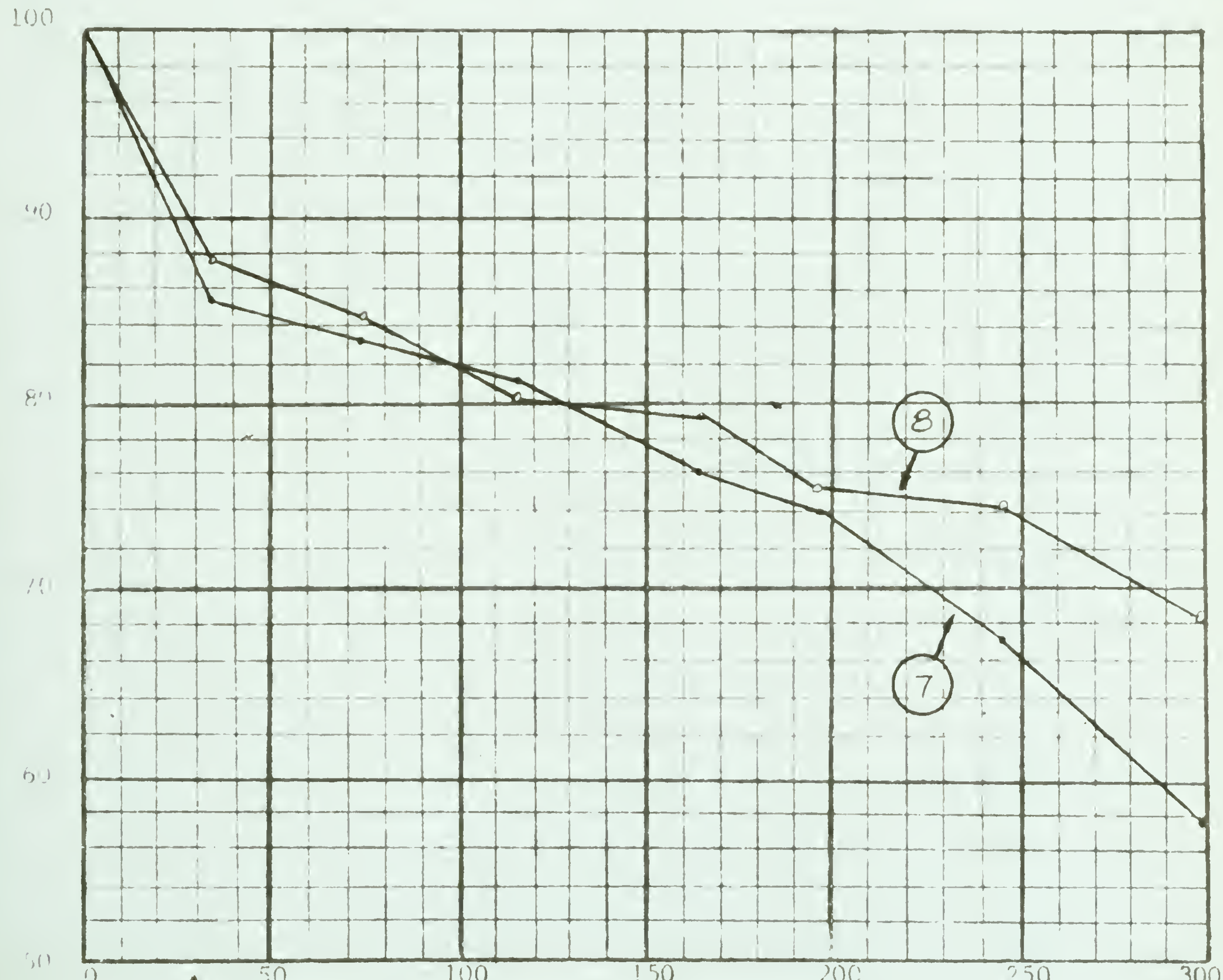


UNIVERSITY OF ALBERTA DEPARTMENT OF CIVIL ENGINEERING CONCRETE DURABILITY TEST	Project Thesis Date Feb. 21 '63 Eng.-Tech. P M

Fine Aggregate F M = 269 Coarse Aggregate 3/4" MAX. Cement HIGH EARLY STRENGTH Admixture AIR ENTRAINED	Method of curing IMMERSED IN SAT. LIME SOLUTION AT 70 ± 3°F Age at test 14 DAYS Beam Temp. Range 0° - 40°F

n	Symbol or w/c	Air Content	Slump	Weight 0 Cycles	Weight, end of test	Durability Factor	Visual Inspection
	6HE-400-0	57	30	9492	9125	578	SEE PHOTOGRAPHS
	6HE-400-0			9573	9185	68.4	

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING



UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
CONCRETE DURABILITY TEST

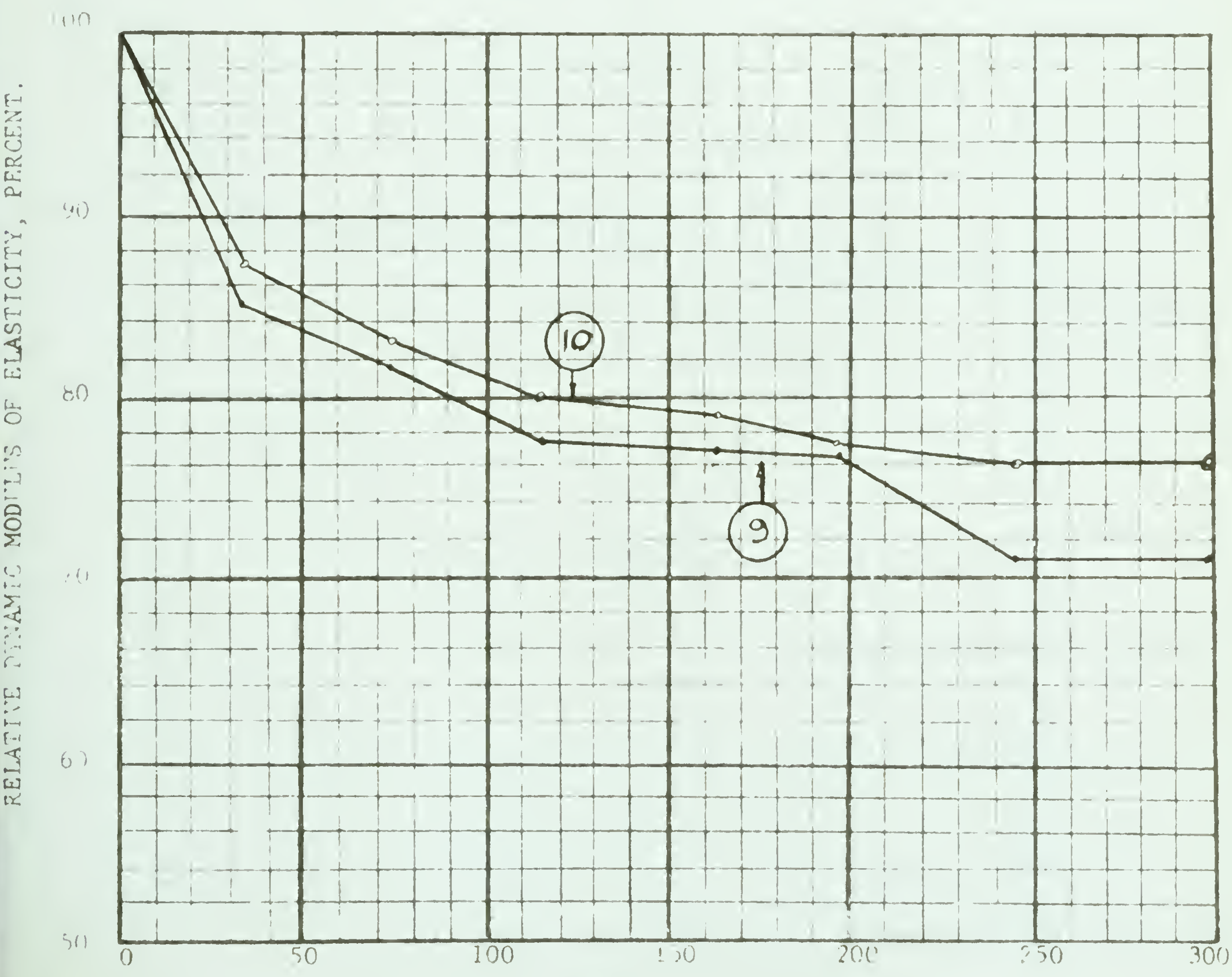
Project THESIS
Date FEB 24/63
Eng.-Tech. P M

Fine Aggregate F M = 2.69
Coarse Aggregate 3/4" MAX SIZE
Cement HIGH EARLY STRENGTH
Admixture AIR ENTRAINED

Method of curing IMMERSED IN SAT. LIME SOLUTION AT 70° ± 2° F
Age at test 14 DAYS
Beam Temp. Range 0° - 40° F.

Symbol or w/c	Air Content	Slump	Weight 0 Cycles	Weight, end of test	Durability Factor	Visual Inspection
6HE 550-C	5.4	3.0	9545	9352	70.9	SEE PHOTOGRAPHS
6HE -550-C			9652	9226	76.1	

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING

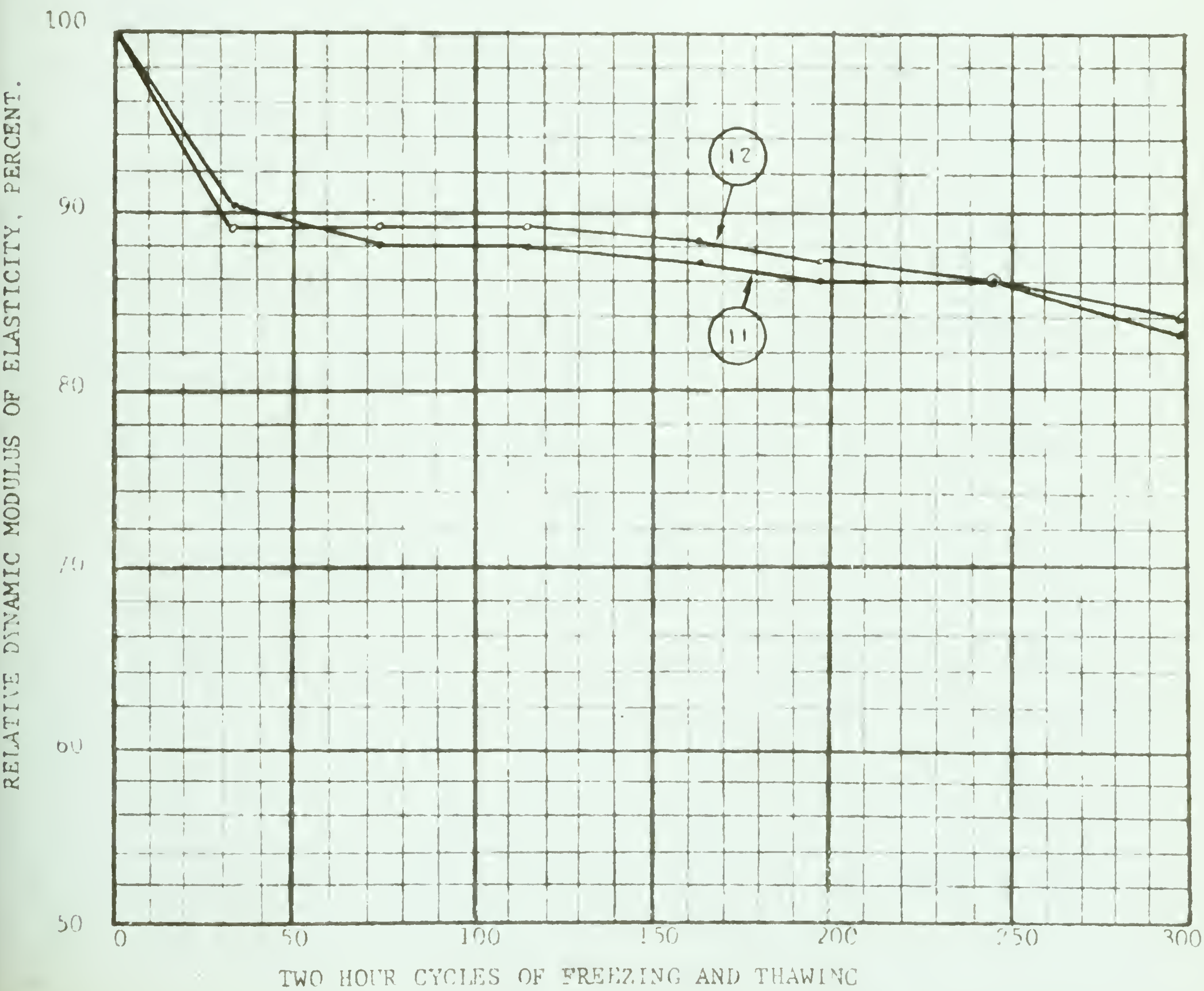


UNIVERSITY OF ALBERTA DEPARTMENT OF CIVIL ENGINEERING CONCRETE DURABILITY TEST	Project THESIS Date FEB. 24/63 Eng.-Tech. P.M.

Fine Aggregate F.M. - 2.69 Coarse Aggregate 3/4" MAX SIZE Cement HIGH EARLY STRENGTH Admixture AIR ENTRAINED	Method of curing IMMERSED IN SAT. LIME SOLUTION AT 70 ± 3°F Age at test 14 DAYS Beam Temp. Range 0 - 40°F

Beam No.	Symbol or w/c	Air Content	Slump	Weight 0 Cycles	Weight, end of test	Durability Factor	Visual Inspection
	6HE-700-0	5.8	3.0	9415	9317	83.0	SEE PHOTOGRAPHS
	6HE-700-0			9502	9400	84.0	

RESISTANCE OF CONCRETE BEAMS TO ACCELERATED FREEZING AND THAWING



APPENDIX C

SAMPLE MIX DESIGN CALCULATIONS

MIX DESIGN CALCULATIONS:

The mix design was carried out in accordance with A.C.I. Committee 613 (1954) "Recommended Practice For Selecting Proportions for Concrete." Reference was made to Table 3 and Table 6 of this A.C.I report. Table 1 presents the physical properties of the aggregate.

For mix designation 6N - 550 - 6

A.C.I. Table 3. - For air-entrained concrete, 3 inch slump, 3/4" max. size of aggregate, require 238 lbs. of water.

A.C.I. Table 6. - Volume of dry-rodded coarse aggregate per unit volume of concrete = 0.62 for a F.M. of 2.69.

Wt. of
Coarse Aggregate = 0.62 x 27 x 96.0 = 1605 lbs.

Volumes

Water	288/62.4	=	4.61
Cement	550/3.15 x 62.4	=	2.80
Coarse Aggregate	1605/2.58 x 62.4	=	9.97
Air - 6%	$\frac{6}{100}$ x 27	=	1.62
			19.00
Fine Aggregate	27 - 19.00		8.00
			27.00

Wt. of fine aggregates 8.00 x 67.4 x 2.59 = 1290 lbs.

Mix Proportions (Sat. Surf. Dry Basis)

Water	288 lbs.
Cement	550 lbs.
Coarse Aggregate	1605 lbs.
Fine Aggregate	1290 lbs.

APPENDIX D

PREPARATION OF CONCRETE SPECIMENS FOR MICROSCOPIC ANALYSIS

Preparation of Surface

The prime factors controlling the validity of the results are the perfection of the finished surface on the concrete specimen and the area of the concrete over which the traverse is made. Care must be exercised in preparing the surface as shelling out of fine aggregate particles and rounding of edges of voids, during preparation of the plane test surface increases the size of observed voids.

The available apparatus permits analysis of specimens 6 inch by 12 inch in size. These specimens can be prepared on the 20 inch diameter lapping wheel. If a larger area is required for analysis, several slabs may be polished to insure adequate sampling.

Procedure

(1) Select the beam to be examined and saw with a diamond blade a slab about one inch thick. The cut should be such that the slab is selected as being perpendicular to the deposition plane of the concrete and also at least one inch away from the end.

(2) After brushing with a soft brush and washing, impregnate the surface to be polished with Carnauba wax.

(3) Using a rotating cast iron lap and No. 80 carbon silicate abrasive, grind the surface so as to remove saw marks.

(4) After the surface is washed and lightly scrubbed with a soft brush to remove grit and loose particles of concrete, it should be again impregnated with Carnauba wax.

(5) Continue grinding on the lapping wheel, switching to finer abrasives. No. 220, No. 400, No. 600. It is extremely important that the surface be washed and lightly scrubbed with a soft brush after each operation to

remove grit and loose particles of concrete. As only one cast iron lap wheel is available, it should also be cleaned after completion of an operation with a particular size of abrasive.

Very little difficulty is generally encountered in preparing surfaces of ordinary concrete that has been cured adequately. However, high air content, high water-cement ratio, lean mixes and deterioration presents problems in surface preparation. For example at very high air content the bubbles tend to coalesce and the thin septa and ridges between the voids are easily lost during grinding. Void parameters determined on such a surface usually are only approximation because numerous chord interceptions must be estimated.

To minimize the difficulties of surface preparation, impregnation of the specimen to strengthen and support the near surface concrete is extremely helpful. Of all impregnating media Carnauba was the most satisfactory. Briefly the method is as follows:

(1) Heat the concrete specimen to 150° C.

(2) Melt the Carnauba wax and brush on the surface of the hot concrete.

(3) After the specimen has cooled to room temperature, start the grinding procedure.

(4) After a satisfactory surface has been prepared, the wax may be removed by heating the specimen (ground side up) to 150° C. and immersing the specimen in xylene in a metal can. Conduct this operation under a hood and avoid breathing the xylene fumes and place the lid on the can after the specimen has been inserted. Gentle agitation of the can will facilitate dissolution of the wax.